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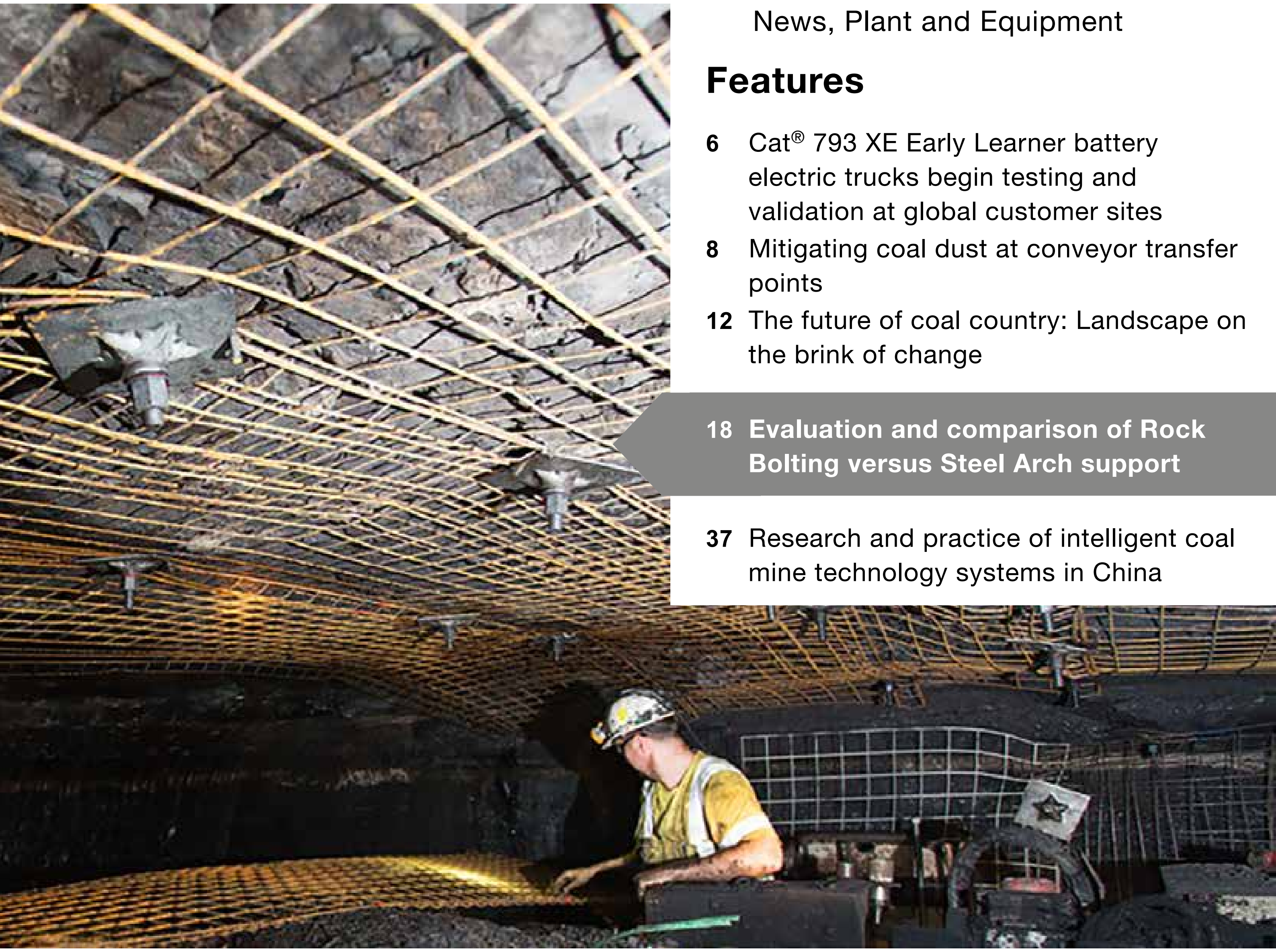

News, Plant and Equipment

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RTL takes up work at Loy Yang

AGL has awarded mining and civil services provider RTL a five-year contract at its Loy Yang coal mine in Victoria.

The contract will see RTL – a Thiess subsidiary – continue to provide rehabilitation, civil and earth works at the La Trobe Valley mine, with the potential for a two-year extension down the track. AGL may also deploy RTL to other locations, if required.

"This new contract continues RTL's long-standing relationship with AGL, and is particularly significant given RTL's involvement with the Loy Yang mine since 1992," Thiess Group executive chair and chief executive officer Michael Wright said.

"As the Thiess Group continues to diversify its services, commodities and jurisdictions, it is critically important that our focus remains on delivering exceptional value for our clients. This contract win is a credit to the team and their focus."

RTL general manager Owen Cavanough said RTL is proud of its continued work at Loy Yang.

"This contract award is testament to RTL's 32-year track record of excellence in safe project delivery and sustainable practices at Loy Yang mine," he said.

"We are proud to continue our presence on this site, supporting Loy Yang Power Station in generating the majority of Victoria's base load power requirements, as well as being able to continue to deliver for AGL and Victorian communities."

India records highest ever coal production in 2023-24, focus on raising coking coal output

India recorded its highest ever coal production of 997.826 million tonnes (MT) in the financial year 2023-24 which represents an 11.71% increase in comparison to the corresponding figure of 893.191 MT in the year 2022-23, according to the year-end review of the Coal Ministry.

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During the calendar year 2024 (up to December 15, 2024), the country supplied about 963.11 MT of coal as compared to about 904.61 MT of coal during the same period of last year with a growth of about 6.47%. This comprised a coal supply to the Power Sector of 792.958 MT as compared to 755.029 MT coal during the same period of last year with a growth of 5.02%.

The coal supply to the non-regulated sector during the calendar year was 171.236 MT as compared to 149.573 MT during the same period of last year with a growth of 14.48%.

The Ministry of Coal has launched 'Mission Coking Coal' to enhance domestic coking coal production to reduce the import of coking coal, keeping in view the demand projection of the steel sector. This mission aims to increase domestic raw coking coal production up to 140 MT by FY 2029-30.

The total domestic raw coking coal production during the financial year 2023-24 is 66.821 million tonnes (MT) while the domestic raw coking coal production target for the financial year 2024-25 is 77 MT.

The target to increase raw coking coal production by FY2029-30 from CIL subsidiaries is about 105 MT by FY2029-30 from 60.43 MT during FY 2023-24.

Modernization and renovation of existing ageing washeries of Bharat Coking Coal Limited (BCCL) and Central Coalfields Limited (CCL), which have surpassed the designed lifespan, for its optimal utilization to make more high-quality coal available in the country.

Supply of coal to the steel sector through the Non-Regulated Sector (NRS) Linkage auction route to promote domestic coking coal for steel production and implementation of reforms in the auction process with the aim of substitution of coking coal import are also being undertaken.

The Ministry of Coal has also auctioned 14 coking coal blocks to the private sector. These blocks are expected to start production by 2028-29.

Queensland eager to accelerate mining approvals

The Queensland resources sector is eyeing streamlined approval processes after a new resources cabinet committee (RCC) was announced.

The establishment of the RCC is part of the new Queensland Government's 100-day plan.

Queensland Natural Resources and Mines Minister Dale Last, who chairs the RCC, said it's considering policies and initiatives to maintain and improve the competitiveness of Queensland's resources sector and the value of its supply chain.

"The committee ensures a coordinated approach and open lines of communication going forward, giving resources companies certainty around their investment decisions," Last said.

The RCC's immediate priority is to streamline approval processes and reduce delays across the sector.

"The first task of the committee is to bring forward solutions that will reduce delays and improve approval time frames, including actions that will reduce process duplication, simplify and align notification processes, and improve consistency in assessment and administration of applications," Last said.

The RCC will provide an update on its progress in February 2025.

"No longer will projects and opportunities languish for years without a decision. Industry, investors, and communities will be given certainty one way or another," Last said.

"Under this government, Queensland is open for business, and we will lay out an ambitious long-term agenda which will see new and expanded mining opportunities across the state.

"We will never take for granted the abundance of our resources and the value the sector delivers to the Queensland economy, nor will we take for granted the more than 60,000 people who are directly employed in the sector."

The RCC is composed of key Queensland Government Ministers, including Deputy Premier Jarrod Bleijie, Treasurer David Janetzki, and Environment and Tourism Minister Andrew Powell.

In the 2023-24 financial year, the resources sector contributed nearly 13% to Queensland's economy, further highlighting its importance.

Dartbrook locks in first coal sales

Australian Pacific Coal (AQC) has seen coal travel from its Dartbrook mine in the Hunter Valley region of New South Wales, marking the operation's first commercial coal sales.

AQC executive chairman John Robinson welcomed the milestone, describing it as a pivotal moment in the company's growth.

"The first sale of commercial quantities of coal from Dartbrook is the most significant milestone successfully achieved by AQC," Robinson said. "With commercial production underway, we now turn our attention to refurbishing the wash plant in early 2025."

The achievement coincides with the International Energy Agency reporting record global coal demand projected to reach 8.7 billion tonnes in 2024. The tonnage is expected to rise until at least 2027.

Robinson noted these favourable market conditions as a promising backdrop for Dartbrook's future.

"This is an exciting time for AQC as coal demand reaches a new record," he said. "Since the completion of the Dartbrook purchase from Anglo American in May 2016, AQC has remained focused on the future of Dartbrook with conviction that the world energy market will continue to grow and demand will increase.

"The substantial coal resource at Dartbrook supports a long mining life, this together with the existing onsite world class infrastructure will allow the Dartbrook coal mine to operate as a Tier 1 mining asset."

Dartbrook's revival underlines its strategic importance in the energy market as AQC positions itself to capitalise on sustained growth in global coal consumption.

AQC has been making strides with Dartbrook ever since it restarted the mine in September, marking the first time the mine had produced coal since it was placed into care and maintenance in 2006 due to operational issues and lower coal prices.

Cat® 793 XE Early Learner battery electric trucks begin testing and validation at global customer sites

Caterpillar announced recently it has achieved the next milestone in the company's battery electric truck development journey, reinforcing its commitment to providing zero-exhaust emissions solutions for customers.

The next generation of Caterpillar's battery electric Large Mining Trucks have arrived at select customer sites for testing and validation. Caterpillar completed building and testing seven Cat® 793 XE Early Learner battery electric trucks at its Tucson Proving Ground facility in Green Valley, Arizona. This marks the second development phase of the company's Early Learner program following the successful demonstration of its first battery electric 793 prototype in November 2022. Caterpillar will also continue testing and validating some of the Early Learner model trucks at its proving ground facility.

Caterpillar group president Denise Johnson says, "We added this Early Learner phase to intentionally send battery electric trucks to customer sites earlier than we have before in our traditional product development process. These Early Learner machines will be used to refine requirements, develop processes and validate both the machine and technology designs. Testing these trucks at our customers' sites will provide invaluable feedback for our battery truck program."

Caterpillar launched its Early Learner program in 2021 to accelerate its development and validation of Cat battery electric large mining trucks with support from key mining customers and Cat dealers. The company expanded the Early Learner program to include Off-Highway Trucks to support increasing demand from the quarry and aggregates industries.

One of the primary objectives of the program is for Caterpillar to collaborate more closely with its customers to better understand the impacts of the energy transition on a mine site's people, processes, infrastructure and technology. The Early Learner phase of the program will be key to witnessing those impacts in real world environments. It will also be critical to validate the enhanced design elements of the 793 XE.

Caterpillar Vice President Brian Weller explains, "In less than two years, we went from retrofitting an existing piece of equipment at our proving ground to designing a ruggedized solution ready for validation at our customers' sites. This was not a small change. Just about everything in the powertrain has been enhanced while still leveraging proven components of our Cat 793 model. With these changes, we still have learning to do with our customers in real-world applications."

Caterpillar's next phase of the Early Learner program will be to integrate multiple electrified trucks at sites, validating the integration of a battery electric fleet with Caterpillar's autonomous and fleet management systems.

CATERPILLAR AFFIRMS LARGE MINING TRUCK PRODUCT LINE COMMITMENT THROUGH THE ENERGY TRANSITION

Caterpillar Inc. (NYSE: CAT) is reinforcing its commitment to deliver product design choices in alignment with customers' operational, sustainability and productivity goals that increase the value of a machine throughout its lifetime. These designs align with Caterpillar's strategy to deliver integrated site solutions to support customers today and through the energy transition.

As the industry looks to the future, Caterpillar is purposefully designing a modular Cat® 793 large mining truck platform with powertrain flexibility. This platform will include diesel mechanical, diesel electric and battery electric options.

Additionally, Caterpillar is leveraging the knowledge and validation acquired through its Early Learner battery electric large mining truck program to drive common platform benefits for its ultra class trucks, including diesel electric and battery electric offerings for the Cat 794, 796 and 798 models.

Caterpillar has a legacy of designing products with customers' current and future needs in mind. For decades, Caterpillar and the Cat dealer network have provided flexible solutions to extend the life of mining trucks, including retrofit kits, update and upgrade programs and full machine rebuilds. These options can extend a customer's equipment to align with current products and technologies while reducing total cost of ownership.

Caterpillar Group President Denise Johnson says, "No matter the powertrain you desire, we will have a solution. Designing and supporting machine platforms that drive commonality, modularity and a seamless experience across our product lines is not new to us. Our large mining trucks are engineered to integrate with the technologies of today and of the future."

All current diesel electric and battery electric large mining truck platforms are also compatible with the recently announced Cat Dynamic Energy Transfer system, providing immediate benefit to mine sites that want to lower their operating costs and greenhouse gas emissions while providing flexibility for the future.

Caterpillar Senior Vice President Greg Hepler said, "Caterpillar recognizes every mine site requires a unique plan to meet their sustainability objectives, which is why we are delivering a suite of integrated energy transition solutions, including machines with powertrain flexibility, energy transfer systems, energy storage and management capabilities, autonomy and fleet management systems. Together with our Cat dealers, we are committed to supporting customers through every step of their energy transition journeys."

Mitigating coal dust at conveyor transfer points

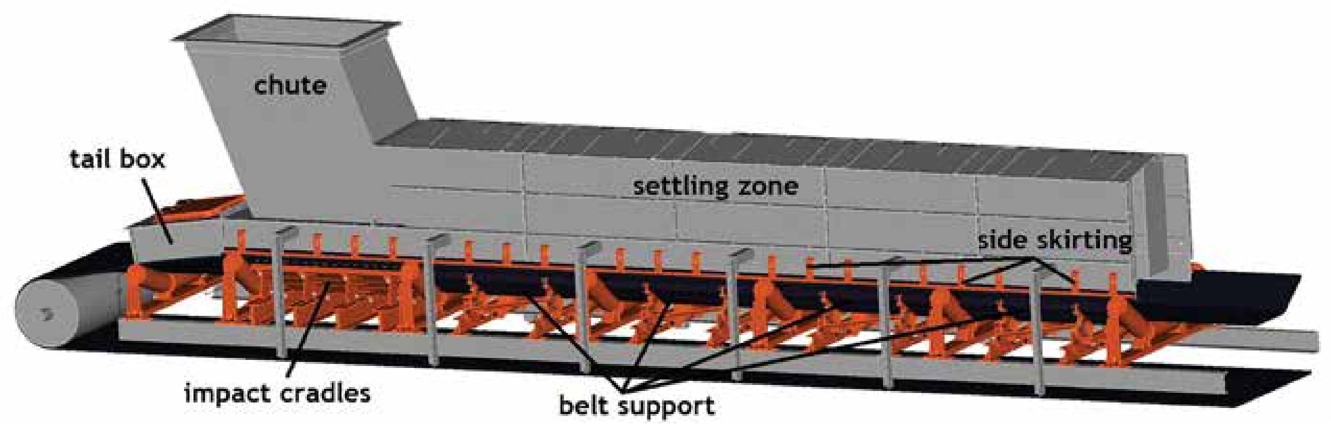

Figure 1: A well designed transfer chute should significantly reduce dust emissions.

There's no question that coal dust is more highly scrutinized and regulated compared to other bulk handling operations due to the health of workers and a high risk of explosions. Ask any coal family and they would agree that the safety and longevity of workers should be a top priority. Controlling dust also makes sense from an operational aspect as it can foul rolling components, machinery, and equipment air intakes requiring extra parts and labor for cleaning and maintenance. All of these factors unnecessarily raise the cost of operation when there are methods and technologies designed to control and suppress dust emissions before they become airborne and cause these risks.

While obvious that one way to reduce coal dust emissions is to reduce the amount of dust created in processing, it isn't always practical or easy to accomplish. There are many dust sources that have to be managed depending on the extraction, haulage, and storage methods. Most of the dust contained in bulk materials is from crushing or grinding to reduce particle size and from transfers from one step in the production process to another such as at conveyor transfer points or discharge onto a stockpile. The hydrophobic properties of coal also make it harder to control dust emissions using water without the addition of expensive surfactant additives.

SURFACE VS. UNDERGROUND OPERATIONS

In surface operations, control of dust is difficult because it happens in the open air and the fracturing of the in situ material creates dust. Typically, the bulk material is loaded into haul trucks at the point of extraction and taken either to a conveyor

Coal conveying, storage, and processing are all activities that generate dust.

transfer point or a crusher. As the material is dumped and crushed, the most effective dust control is the use of water or if water addition to the material is a problem, foam is used. Water isn't as effective as foam but is often preferred due to the cost of foaming chemicals. There are some residual effects of water but they are usually short-lived.

In underground extraction, water is often used at the face and conveyor transfer points to control dust. When water cannot be used, methods such as in mining salts, ventilation and modular dust collection are options.

CONVEYORS

Conveyors are a major source of dust emissions, but they can also aid in reducing fugitive dust. For example, in pit crushing and overland conveying in a surface coal mine, there is reduced total site dust generation compared to truck haulage. Coal is easily windswept and in some cases may require an enclosed conveyor belt system such as a fold belt, pipe conveyor, or air-supported conveyor.

When the haulage involves a conveyor belt, dust generation is a function of the loading and discharge as well as how it is managed. Closed conveyors are very useful for preventing contamination and protecting the cargo from the elements, but they still have to be opened and closed for loading and discharge. Passive dust reduction strategies include: [Figure.1]

- *Shorter or directed drops* – Transfer chutes over loading zones that decrease the impact of cargo on the belt below reduce the amount of turbulence within the loading zone, lowering the amount of dust released.

- *Managing the flow* – Although rock boxes can work, they can also be prone to clogging, so experienced engineers recommend a sloping system that slows material to minimize impact and induced air, as well as loads in the center of the belt for less shifting and improved belt training.

- *Preventing belt sag between idlers* – The belt can dip slightly between idlers, creating gaps between the belt and skirting, causing the release of dust and fines in the loading zone. Using an impact cradle with shock-absorbent polyurethane bars reduces impact strain on the belt and creates an even belt plane with no gaps between the skirting and belt. Cradles can extend along the entire length of the stilling zone.

- *Fully enclosed transfers* – By completely enclosing the loading and settling zone, dust is contained. Items like dust curtains and dust bags can then be added to control airflow and capture dust.

LOWER BELT SPEEDS

There are many suggestions for belt speeds based on the properties of the bulk material. ANSI/CEMA 550-2003 Classification and Definitions of Bulk Materials lists miscellaneous properties of bulk materials that would contribute to a decision to use a lower belt speed and may be windswept as part of its classification code system include:

- B-1 Aeration-Fluidity
- B-6 Degradable-Size Breakdown
- B-8 Dusty
- B-20 Very Light and Fluffy

With lower belt speeds, the belt width has to increase to convey the same tons per hour creating a capital cost vs operating cost dilemma. Many sources suggest belt speeds of 2 m/s (394 fpm) or less for reducing dust generation.

If a conveyor is being designed for an extended lifetime, then it is worth the effort to closely compare the capital savings from a higher-speed belt to the long-term costs of maintenance, cleanup, and safety. There are clear relationships between increased cleanliness, fewer safety incidents, and more reliable production so the tradeoffs should be examined closely. Foundations™ for Conveyor

Enclosed conveyors reduce exposure to wind with fewer dust emissions leaving the site.

Impact cradles can reduce damage and prolong belt life over standard impact idlers.

Uncontrolled drops into stockpiles can spread dust for long distances.

Safety – a comprehensive textbook for safe conveyor operation written by Martin Engineering -- provides a detailed methodology and data sources for including direct and indirect costs in the financial analysis in section six.

COAL DUST AND BELT TENSION

Similarly, at a critical speed, the bulk material loses contact with the belt at the idler and is launched into the air, falling back onto the belt at a slightly lower speed than the belt. This splashing action opens the profile, creating induced air flows that can release dust, creating turbulence, impact, and degradation as the material lands and returns back up to belt speed. Keeping the belt sag to 1% between idlers is a frequent specification. Usually, the concerns in conveyor design from these belt sag phenomena are the added belt tensions required to overcome the frictional losses.

Often overlooked in a dust reduction strategy are design choices that can minimize dust creation from the undulations of the bulk material on the belt as it is transported. Managing belt tension so the sag between idlers is minimized reduces the effects of material trampling and splash. Material trampling is the particle-to-particle movement created by the change in the bulk material profile as it goes over the idlers. Trampling and splash can be a source of dust generation given the large number of times the cargo passes over idlers every hour. The higher the belt tension, the lower the trampling loss.

COAL STORAGE

Controlling dust at the storage location is another challenge. Large stockpiles are impractical to enclose in buildings and are often stacked out and reclaimed by machinery that generates additional fines. Open stockpiles are subject to the weather where some bulk materials degrade upon exposure to the atmosphere and some materials will revert to a solid state when exposed to humidity or rain. Those materials that can be wetted often use water sprays to reduce windblown dust. Other strategies include wind fences and compacting the pile.

Discharge onto the pile is a source of dust release as the material flows from the delivery equipment, often a conveyor, onto the pile. Cascading or telescoping chutes can be used to reduce the release of dust in these cases. If the material is easily broken, the drop height from discharge to the pile or between cascade shelves can create additional dust from impact degradation. One unexpected source of dust emissions can be the site layout. For example, if a slope conveyor going from the stockpile into a storage bin or building is orientated in line with the prevailing winds in a high wind locale, the wind flowing up the conveyor will overwhelm dust control strategies by creating positive pressure throughout the conveyor enclosures.

Coal is never going to be a 100% dust-free operation but good transfer point design can make it safe.

BEST PRACTICES: ENCLOSE THE SYSTEM

If the material stream can be constrained so that it does not open up when discharged, the amount of air induced into the transfer point is reduced. As the material particles spread out, it creates a low-pressure area in the spaces which induces airflow into the transfer point.

The amount of dust that can become airborne is directly proportional to the volume and speed of the airflow through the transfer point. If the openings in the chute work are restricted to the practical minimum, the inward airflow is restricted. A useful dust control strategy is to capture the material shortly after discharge and keep the stream coalesced as tightly as possible to reduce induced air.

There are a number of Discrete Element Modeling (DEM) software programs specifically designed for the design of material flow through chutes and there are specialty chute manufacturers that specialize in these techniques. These chutes work best with materials of consistent size and adhesive and cohesive properties like coal. Wear on the chute surfaces may be accelerated but this can be offset with a maintenance-friendly design for quick and easy change out of wear surfaces.

CONCLUSION

Much emphasis is placed on planning the mine to maximize profitability but little attention is placed during the initial feasibility studies on how the layout can affect dust creation and emissions. Conveyor transfer points have a history of being drafted rather than designed. Design tools are now readily available to address these critical details. How the conveyor is operated and maintained also has a significant effect on dust generation and release.

R. Todd Swinderman
President Emeritus / Martin Engineering

R. Todd Swinderman earned his B.S. from the University of Illinois, joining Martin Engineering's Conveyor Products division in 1979 and subsequently serving as V.P. and General Manager, President, CEO and Chief Technology Officer. Todd has authored dozens of articles and papers, presenting at conferences and customer facilities around the world and holding more than 140 active patents. He served as President of the Conveyor Equipment Manufacturers' Association (CEMA) was the editor of CEMA's 6th and 7th editions of Belt Conveyors for Bulk Materials, The Design Guide for Belt Conveyors. Todd is active on several CEMA committees including Chair of the Bulk Safety Committee and is a member of the ASME B20 committee on conveyor safety which set U.S. conveyor safety standards. Swinderman retired from Martin Engineering to establish his own engineering firm, currently serving the company as an independent consultant.

The future of coal country: Landscape on the brink of change

A drive through Montana's coal country starts at the Little Bighorn Battlefield and ends in an uncertain future.

The road rolls over prairie grasslands of the Crow Indian Reservation, just south of the Absaloka coal mine. Then it climbs the Wolf Mountains and crosses into the Northern Cheyenne Indian Reservation amid tumbling sandstone formations tipped with scoria, a clay formation toasted red by prehistoric burning in underground coal seams. At Lame Deer, the road bends northeast through hills cut by Rosebud Creek, until suddenly coming over a rise to reveal the four smokestacks of Colstrip's coal-fired power plant.

It's harder to see the actual coal unless you're in an airplane. The strip mines between Colstrip and Crow Agency expose long black beds of burnable carbon. From this northern edge of the Powder River Basin south into central Wyoming lies 41% of the United States' coal supply. For the past century, it has fed the nation's energy demand.

Nearly all that demand has vanished. The Absaloka coal mine on the Crow Reservation lost its last utility customer last year. Colstrip's power generating plant is losing utility customers as public utilities switch over to renewable energy sources such as wind and solar.

A switch to renewable energy could happen here, too. Tens of billions of federal and private dollars stand ready to reshape Montana's coal country, if its residents choose a path forward. Three communities central to the region's identity – Crow, Northern Cheyenne and Colstrip – have remarkably different attitudes toward that future.

That leaves some big choices for people in Montana's coal country. The decisions they make will be refracted through economic forces beyond their control, as well as cultural and traditional perspectives that define what it means to live in coal country. And as this 2024 election year winds to a close, those residents can make their opinions known through their votes on races from tribal council seats to the White House.

SAME VIEW, DIFFERENT VISIONS

Where someone stands on the future of Montana's coal industry depends on where they sleep.

Although their 444,000-acre reservation has 23 billion tons of proven reserves, the Northern Cheyenne Tribe has declined to exploit its coal. Many tribal members work at Colstrip's mines or power plant. But they have rejected past proposals for developing industrial-scale coal operations on the reservation.

But the impact of the nation's ongoing energy transition has been much greater – nearly 1,000 jobs connected to the Crow tribal government have also lost their coal royalty revenue stream since 2017. While much of Indian Country in Montana has been a Democratic voting bloc, the Crow have ties with Republican Sen. Steve Daines, who has pushed a bill in Congress to give the tribe an option to share royalties from the Signal Peak coal mine just north

The Absaloka coal mine just north of the Crow Indian Reservation provided royalties that supported about 1,000 tribal government jobs. It ceased production in April 2024 after its last customer ended its contract. Credit: Ben Allan Smith / Missoulian

of the 2.2 million-acre Crow Reservation through a mineral rights swap.

In Colstrip, decades of political influence has kept the state government focused on keeping the traditional coal industry viable. That's produced beneficial rulings at the Public Service Commission for NorthWestern Energy to keep coal in its portfolio, provided economic transition programs, and stalled efforts to develop renewable energy projects that might replace coal.

Those alternatives run the buffet line from $43.7 million for rooftop solar panels on private homes in tribal, low-income and economically distressed parts of Montana to a $700 million federal contribution to a $3.2 billion transmission line project that could link wind energy producers from North Dakota to Oregon.

To spur more development, the federal Energy Infrastructure Reinvestment Program has $5 billion in direct loan authority backed by $250 billion in loan guarantees. Fleshing out the federal investments are tax incentives for renewable energy programs, infrastructure grants for building projects, job training for new industries and remediation funds to clean up old coal mines.

If it all gets spent, the federal bill could cost $1 trillion. The Biden White House estimates that the benefits will total more than $5 trillion in worldwide ecological and economic benefits by 2050.

But people all across coal country don't appear to be lining up for the next new thing.

For a variety of reasons, the federal spending opportunities have had difficulty getting attention. Part of that stems from the long allegiance to coal as a source of jobs, purpose and identity. Part comes from distrust or unfamiliarity with new technology. And perhaps some signifies a defense against the sheer blizzard of controversy surrounding global warming, economic upheaval, Indigenous/white culture friction and plain old change.

The landscape itself doesn't offer many hints at a future direction. The massive Yellowtail hydroelectric dam on the Bighorn River would remain, but without coal, not much else points toward an economic future. Southeast Montana is not among the state's most productive farming or cattle acreage. It lacks the tourist magnetism of the western part of the state. Any industrial production would face miles of transport expenses to reach a distribution hub like Billings. As is, about 60% of the price Pacific Coast power plants pay for Montana coal goes to cover the railroad shipping expense.

And while the wind blows hard and the sun shines bright across this bit of Montana, renewable energy doesn't appear to offer the same community impact that a climate-cooking coal mine does. As one Northern Cheyenne resident put it: "Ever seen a wind farm with a parking lot?"

The Absaloka coal mine lost its last customer last year. When the mine stopped producing last spring, about 120 Crow Indians lost jobs with mine owner Westmoreland Coal. Credit: BEN ALLAN SMITH, Missoulian

TRIBAL PERSPECTIVES

Jason Small made that observation over a piece of coffee cake on the patio of the Custer Battlefield Trading Post, just across Highway 212 from the Little Bighorn Battlefield National Monument. That day he was wearing a sleeveless T-shirt and overalls, on his way to a boiler repair job in Helena. On different days, he'd be in a suit and tie as a Republican legislator representing Busby and the Northern Cheyenne Indian Reservation. He also wears the hat of the executive secretary for the Montana AFL-CIO, the state's biggest union network.

"There's night-and-day differences between the two tribes," Small said of the Northern Cheyenne and Crow. "Energy policy, politics, climate, everything. The Crow opened their mine in 1974, and it was putting $50 million, $60 million a year into their budget in the Obama years. On Northern Cheyenne, the traditional people didn't want to mine coal. There was a popular vote, and everyone decided to leave it alone."

The corporations developing the coal paid high wages for hard work, averaging $75,000 a year. They also provided scholarships for kids to go to college or get job training. The royalties from state coal severance taxes flow back to local governments in lieu of local mill levies, or come back circuitously through the Montana Coal Tax Trust Fund. In 2023, that fund (enshrined in the state Constitution) held about $1 billion. However, by 2024, Montana tax collectors were receiving more from cigarette sales than from coal royalties.

"People don't want to lose the opportunities they have," Small said. "Something new comes along, they don't want to take a step backward."

But coal may not be able to take a step forward.

CAN COAL COMPETE?

Next to the long, straight seams of coal currently under excavation west of Colstrip, an observer can see a smaller series of gouges in the earth that look a little like a Wi-Fi symbol. Those are the revegetated remains of Northern Pacific Railroad coal mines from the turn of the 20th century, when this part of Montana started playing a part in the nation's industrial development.

Montana's coal took an even more prominent role in the 1970s, after scientists confirmed the link between the more sulphureous Appalachian coal and acid rain, which was poisoning lakes across the eastern United States. The subbituminous coal of the Powder River Basin doesn't generate as much heat when burned as the bituminous coal of West Virginia, but its exhaust has less sulphuric acid.

Although Montana encloses most of the Powder River Basin deposit, Wyoming digs much more of that coal – 244 million tons in 2022. Montana added about 30 million tons that year, despite sitting on 74 billion tons of recoverable reserves stretching from Wyoming to the Canadian border.

Nevertheless, coal of either type produced the single

The Pryor Mountain wind farm just south of Crow Agency produces 240 megawatts of power at around 5 cents. A wind farm can generate power for 3 to 6 cents per kilowatt hour. Credit: BEN ALLAN SMITH, Missoulian

greatest amount of greenhouse gases driving up global temperatures. Oil company researchers in the 1970s connected the dots between burning fossil fuels and global warming. But those same companies, including ExxonMobil, mounted decades of counter-campaigns disputing the danger of climate change while burying their own science.

Growing awareness of climate-change impacts such as longer wildfire seasons and shorter ski seasons led to global social pressure to move away from fossil fuel burning. That included decisions by Colstrip power clients such as Puget Sound Energy and Avista Corp. to drop their investments in Montana coal in 2025. Those moves were prompted by state law changes in Oregon and Washington requiring the states' energy utilities to seek greener energy sources.

At the same time, other market forces undercut coal's economics. Methane, commonly known as natural gas, costs around 6 cents a kilowatt hour, while coal-fired electricity costs upwards of 14 cents. Both fossil fuels face growing opposition because their burning warms the atmosphere, scrambling planetary weather patterns and intensifying natural disasters like hurricanes and wildfires.

A wind farm can generate power for 3 to 6 cents per kilowatt hour. The Pryor Mountain wind farm just south of Crow Agency produces 240 megawatts of power at around 5 cents per kilowatt. An 800-acre solar farm on the Billings rims adds another 80 megawatts.

A megawatt of electricity powers about 800 homes in the northwest United States. Renewable energy sources are becoming more affordable and reliable. In September, wind and solar generators in the four-state region that covers Colstrip produced 6.6 gigawatts of electricity, while coal facilities in the same region produced 7.1 gigawatts.

A solar farm north of Billings in August. Regionally, the solar and wind farms between Pryor Mountain and Billings now produce more day after day than Colstrip does. BEN ALLAN SMITH, Missoulian

Jason Small is a Republican legislator representing Busby and the Northern Cheyenne Indian Reservation. "There's night-and-day differences between the two tribes," Small said of the Northern Cheyenne and Crow. "Energy policy, politics, climate, everything. The Crow opened their mine in 1974, and it was putting $50 million, $60 million a year into their budget in the Obama years. On Northern Cheyenne, the traditional people didn't want to mine coal. There was a popular vote, and everyone decided to leave it alone." Credit: BEN ALLAN SMITH, Missoulian

For its part, Colstrip generated only half its 1.4-gigawatt capacity on 12 days of that month. Whereas wind and solar had only 14 hours when they produced less than Colstrip's full potential. In other words, even when the wind wasn't blowing or the sun shining, wind and solar out-generated Colstrip's coal furnaces.

MONEY AND VOTES

Incumbent U.S. Sen. Jon Tester, a three-term Democrat, was part of the final negotiating team that produced the bipartisan Inflation Reduction Act and Bipartisan Infrastructure and Jobs Act – legislation offering billions of federal dollars for investment in coal country. Tester's Republican challenger, political newcomer Tim Sheehy, was recruited by Sen. Steve Daines and the National Republican Senatorial Committee Daines chairs. National polling shows Montana's Senate race "leaning Republican."

That makes getting the attention of Indian Country essential to both candidates. Native Americans make up about 7% of Montana's million residents – the only demographically significant minority in an otherwise overwhelmingly white state. But while voter turnout for tribal elections tends to be strong on reservations, that hasn't translated to predictable results in state and federal races. And although Native Americans nationally tend to vote Democratic, tribal differences such as those seen on the Crow and Northern Cheyenne reservations make the voting bloc murky.

Colstrip has been a Republican stronghold for decades, as have most of the surrounding counties. As president, Republican Donald Trump promised to "bring back coal." However, his administration saw the closure of 75 coal-fired power plants and the loss of about 13,000 coal jobs nationally. In Montana that included the closure of Colstrip Units 1 and 2, the Decker mine, the Lewis and Clark Generating Station in Sidney and the Savage mine. It also included the bankruptcies of Westmoreland, Cloud Peak, Lighthouse and Talen.

Democratic President Joe Biden has actively supported unions and the heavy infrastructure spending that are trying to bring renewable energy projects and dollars to Montana's coal country. But he also imposed new air pollution regulations that NorthWestern Energy officials claim will force premature closure of Colstrip. On Oct. 4, the U.S. Supreme Court declined to block Biden's rules.

Many of those economic and political forces will play out within the next year. The election takes place Nov. 5. In his City Hall office, recently rebuilt with local coal revenue, Colstrip Mayor John Williams said the changes can't be ignored.

"We don't want to be defined by the stacks," Williams said, referring to the four landmark exhaust towers of Colstrip's generating station. "We're more than that."

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Evaluation and comparison of Rock Bolting versus Steel Arch support

This study investigates the feasibility of rock bolting support in an underground coal mine gallery with a thick coal seam. The Ömerler underground coal mine working area, owned by the West Lignite Enterprise (GLI) of the Turkish Coal Enterprises (TKI), was selected for this purpose. Longwall top coal caving (LTCC) is implemented as the production method in the Ömerler underground coal mine. Field and laboratory studies were conducted to determine rock mass and rock material properties, followed by experimental, empirical, and numerical analyses based on the acquired data. The obtained design results were evaluated using a resin-grouted rebar (RBR) rock bolting system and steel arch support (SAS) pilot application areas. The numerical modelling results conducted using the Fast Lagrangian Analysis of Continua 3D (FLAC 3D) (v6.0) program indicated less displacement and secondary stress change in the RBR-supported zone compared to the SAS-supported zone. In situ measurements also demonstrated that RBR provided more successful support to the roof during coal production activities. The findings suggest that RBR is a more effective solution when evaluating the feasibility of rock bolting support systems in underground galleries with thick coal seams at the Ömerler underground coal mine. This study emphasizes the importance of more sustainable and safe support systems to enhance operational efficiency in the coal mining industry.

Coal, a significant component of global energy production, continues to play a crucial role in the world economy. In 2022, global coal demand reached its highest level to date. While this trend persists, there is a need to enhance efficiency and undertake improvement efforts in coal mining to contribute to the overarching goal of energy sustainability. The rise in global coal demand is causing a depletion of open-pit reserves where coal production takes place, leading to a transition towards deeper underground mining operations. This transition involves creating galleries for underground coal production, with a particular focus on faster and more dependable support systems, to reinforce sustainability and operational efficiency within the coal mining industry.

In recent decades, underground coal mines have adopted mechanized excavation systems, particularly employing the longwall mining technique, to facilitate high-volume coal production. However, this implementation has resulted in the formation of numerous mine galleries. The traditional roof support system utilizing steel sets in these galleries can adversely impact their daily advancement rates, unit costs, and safety, especially in rock mass environments characterized by very weak, weak, and moderately strong strengths.

Over the past four decades, there have been notable advancements in rock bolting support systems, driven by improved insights into load transfer mechanisms and the evolution of rock bolting technology.

Distinguished from traditional support systems like steel sets, this system facilitates faster advancement rates, reduced unit costs, and enhanced safety through its active support capabilities. In contrast to passive support systems such as steel sets, rock bolts engage more rapidly with the rock mass to initiate their supporting function, resulting in less deformation and facilitating safer and swifter gallery advancement. Consequently, it has been successfully implemented as the primary supporting element in underground coal mines across various regions globally.

In underground coal production activities, especially in thick coal seams, detailed preliminary design studies should be conducted for the proper reinforcement of gate-roads with rock bolting. The empirical approaches, commonly used in project works today, are developed by combining observations, measurements, experience, engineering intuition, and judgments. These approaches can provide predictions for support parameters such as rock bolt length and spacing, dimensions and intervals of steel sets, and thickness of shotcrete for the stability of underground openings. Eleven different empirical approaches can provide design outputs for rock bolting support. It is known that six of these approaches are based on the widely used RMR rock mass classification system, two are based on the widely used Q rock mass classification system, and two are based on the RQD system. Additionally, there are two different design approaches based on Panek and the number of discontinuity sets and the dip angle of the discontinuities.

Mathematical-based and assumption-dependent numerical design approaches have been developed to determine stress and deformation behaviours in the opening zones of underground and surface rock engineering excavations. In today's design practices, two- and three-dimensional numerical analysis programs developed in many significant studies are utilized. In the two- and three-dimensional models presented in numerical analyses, alongside rock material and rock mass parameters, input parameters for support, such as rock bolt length, spacing, and shotcrete thickness, need to be initially defined. The necessity to perform hundreds of numerical simulations to determine unknown optimal support parameters is considered a serious problem. Additionally, the presentation of field stresses and displacement quantities, which cannot always be measured, using numerical analyses necessitates the careful use of numerical approaches, especially in complex field conditions.

This study aims to analyse the feasibility of rock bolting in an underground coal mine gallery with a thick coal seam, which is currently using steel supports, through numerical modelling. Within this scope, the Ömerler Underground Mine, located in the West Lignite Enterprise (GLI), which is a part of the Turkish Coal Enterprises (TKI) and situated in the Tavşanlı district of Kütahya province, has been selected as the study area. Coal production in the Ömerler underground coal mine, which possesses a thick coal seam, is carried out using mechanized mining methods. The mining operation, which utilizes the longwall top coal caving method (LTCC) as its production method, employs a self-advancing hydraulic powered roof support system (shields) within the coal face while using a steel arch support system in the main haulage galleries and the gates belonging to the panels.

To examine the applicability of rock bolting support in the mentioned headgate, in situ and laboratory studies were conducted to determine rock mass and material properties. Based on the obtained database, empirical and numerical analyses were performed to design an appropriate rock bolting system for the field. FLAC3D v6.0 finite difference method modelling software was used for numerical modelling. With the resulting design, the resin-grouted rebar rock bolting system (RBR) and steel arch support (SAS) were implemented in the pilot application area. In situ monitoring activities using various methods were conducted to assess the performance differences between the rock bolting systems and the steel arch support system.

METHODOLOGY

Study Site

TKI-GLI Ömerler Underground coal mine is located in the town of Tunçbilek (Tavşanlı district of Kütahya province) in Turkey (**Figure 1**).

The rock units within the Tunçbilek series are grouped into three main categories, namely clay stone, calcareous marl, and marl. The clay stone formation, which surrounds the coal seam, is also subdivided into three subgroups. These subgroups consist of the soft clay layer located immediately above the coal seam with a thickness ranging from 20 to 50 cm, the roof clay forming the main roof rock of this

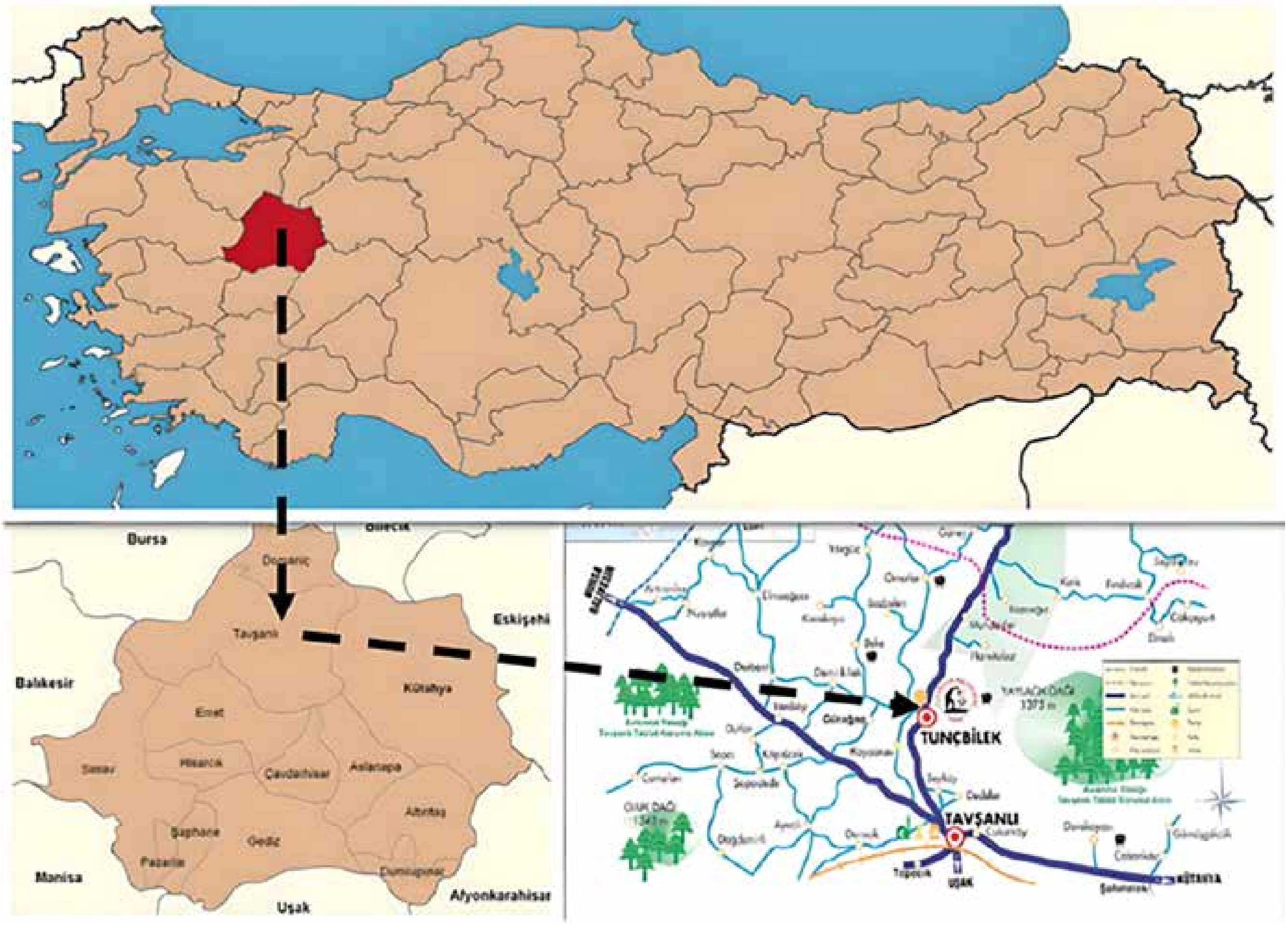


Figure 1: Location of study site.

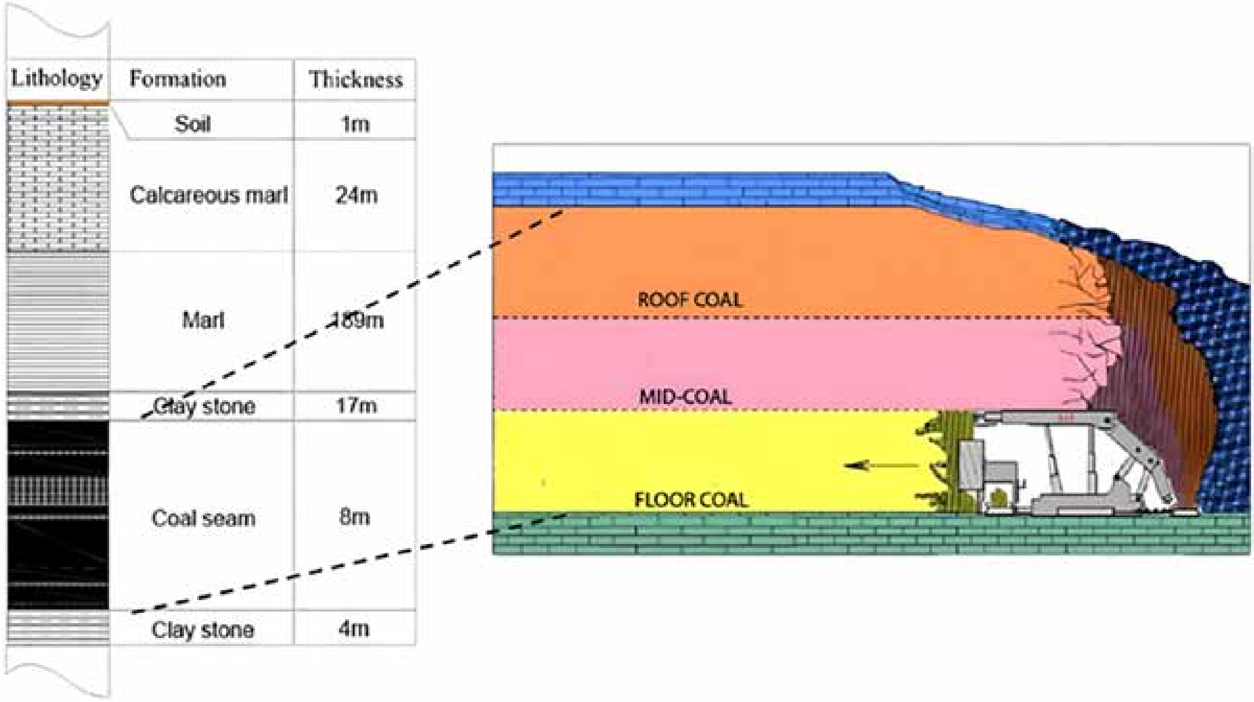


Figure 2: Lithology of geological structure.

formation, and the floor clay formations situated beneath the coal seam (**Figure 2**).

In the GLI Tunçbilek coal basin, underground coal production has been carried out in the Ömerler-A section. In this underground mine, a fully mechanized mining system is used, and coal extraction is performed using the LTCC method. The thick coal seam, averaging 8 m in thickness, is excavated using a single-pass method for the lower 3.5 m, while the remaining approximately 5 m at the roof level is extracted through the caving process. The cross-sectional view of the mining method is presented in **Figure 2**.

In the basin, strata have generally dip angles ranging from 5 to 20° toward the northeast. The coal reserve within the study area is estimated to be around 18 million tons. The coal seam thickness varies between 5 and 12 m, with an average thickness of 8 m. The coal seam contains clay partings of approximately 15-30 cm thickness at various levels. The deepest working section in the underground mine is located at an elevation of +469, and the thickness of the overlying strata is approximately 330 m.

The study area is the A6 longwall panel in the Ömerler underground coal mine (**Figure 3**). Rock mass and rock material property determination studies for coal and surrounding rock were carried out in the A1, A2, and A6 longwall panels. Empirical design studies and numerical modelling studies, rock bolting applications, and monitoring activities were conducted in the headgate of the A6 panel (**Figure 3**).

Determination of Rock Mass and Rock Material Properties

In order to design and implement rock bolting support for the A6 longwall panel gate-roads, a series of in situ and laboratory investigations were executed to ascertain rock mass and rock material properties. These studies not only encompassed the A6 longwall panel where the actual implementation occurred but also included examinations in the A1 and A2 longwall panels, where preparatory and production activities were concurrently in progress. Drilling operations and block extraction studies were carried out in specific underground zones to assess rock mass and material properties, as well as for classification studies.

Underground drilling activities were carried out in the production panel, encompassing four directions. Additionally, 50 blocks were extracted from the A1 and A2 panels and transported to the rock mechanics laboratory for subsequent sample preparation. Schmidt hammer rebound hardness tests (N-type), point load strength index tests (Is50), and plate loading tests were systematically performed in the A1, A2, and A6 panels.

All rock mechanics tests were executed on the rock material samples derived from the transported blocks and drilling cores. The resulting database is comprehensively presented in **Table 1**. Field-based Geological Strength Index (GSI) classification studies were conducted in the A1 preparatory gallery to classify the rock mass. The determined values, coupled with outcomes from other rock mass classification systems, were computed and are presented in **Table 2**.

Accurate predictions regarding the stability of underground openings require an understanding of the mechanical properties of the rock mass and measurements of principal stresses in the environment. In line with this, studies on principal stress analysis were undertaken within the A1 longwall panel of the Ömerler underground coal mine (**Figure 4**).

Following Aydan's method for determining principal in situ stresses through the fault slip approach, the analysis outcomes revealed that the maximum horizontal stress is predominantly aligned in the north-south direction. Additionally, it was established that at a depth of 300 m, the most significant horizontal principal stress (P_H = 6.74 MPa) in the A1 panel aligns parallel to the gate axis.

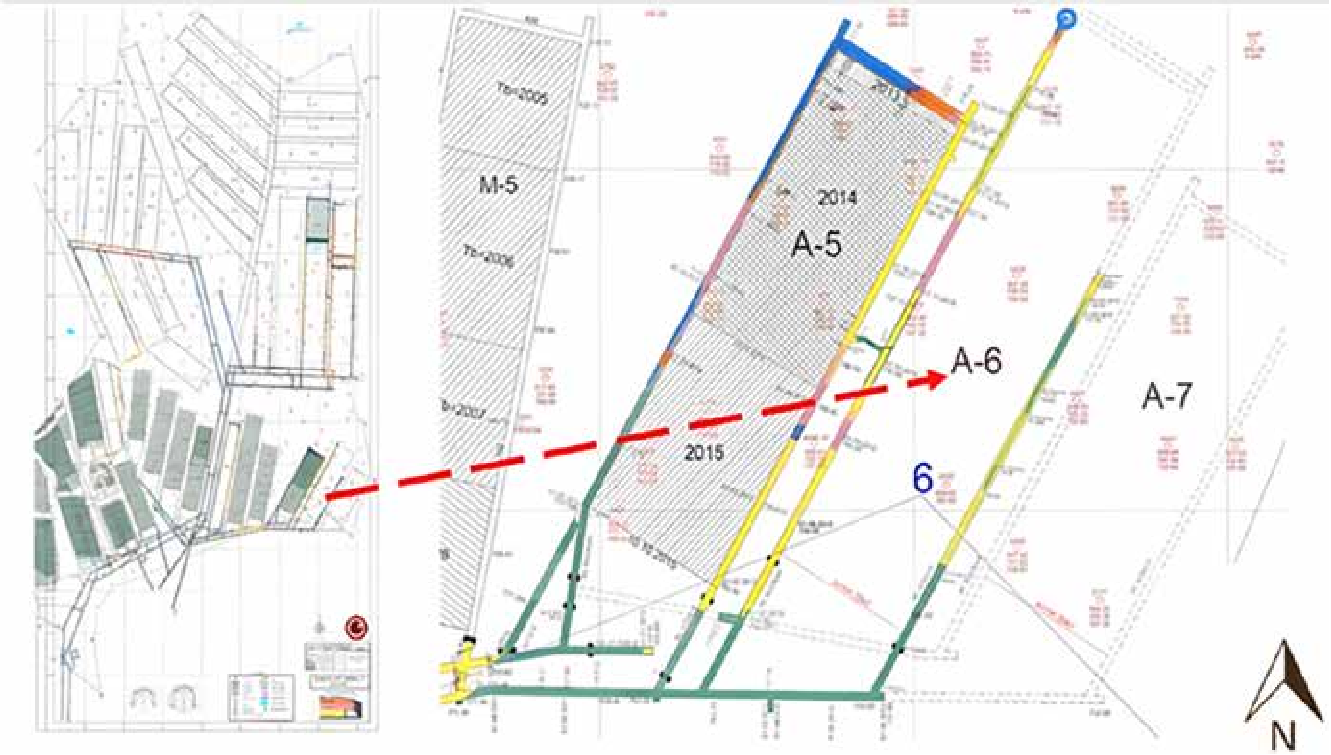


Figure 3: The view of the A6 panel which was considered in rock bolting support design studies on the mine layout.

Table 1: Rock material properties

Data	Symbol, unit	Coal	Roof rock	Floor rock
Uniaxial compressive strength (UCS)	σci (MPa)	8.84	10.66	12.04
Tensile strength (Indirect-Brazilian)	σt (MPa)	2.30	8.31	8.91
Cohesion	c (MPa)	0.401	0.487	0.419
Friction angle	φ (°)	31.03	24.32	25.44
Modulus of elasticity	E (MPa)	2663	3198	3612
Poisson’s ratio	υ (-)	0.18	0.264	0.27
Bulk density	ρ (g/cm3)	1.26	2.00	2.12
Natural unit weight	γ (kN/m3)	12.40	19.60	21.7
Slake durability index	Id2 (%)	91.00	98.89	98.55
Point load strength index	Is(50) (MPa)	0.51	0.70	2.38

Table 2: Rock mass properties

Data	Symbol, unit	Coal	Roof rock	Floor rock
Geological strength index	GSI	35	43	47
Rock mass rating	RMR	32	44	47
Rock quality designation	RQD	50	60	70
Quantitative rock mass rating	Q	0.37	0.99	1.16
Uniaxial compressive strength	σcm (MPa)	1.481	1.244	1.543
Tensile strength	σtm (MPa)	0.004	0.024	0.037
Cohesion	cm (MPa)	0.401	0.487	0.419
Friction angle	φm (°)	31.03	24.32	25.44
Modulus of elasticity	Em (MPa)	302	625.99	920.07
Poisson’s ratio	υ	0.18	0.264	0.27
Bulk modulus (K = [E/3(1-2υ)])	K (MPa)	157.29	442.08	666.72
Shear modulus (G= [E/2(1+υ)])	G (MPa)	127.97	247.62	362.23

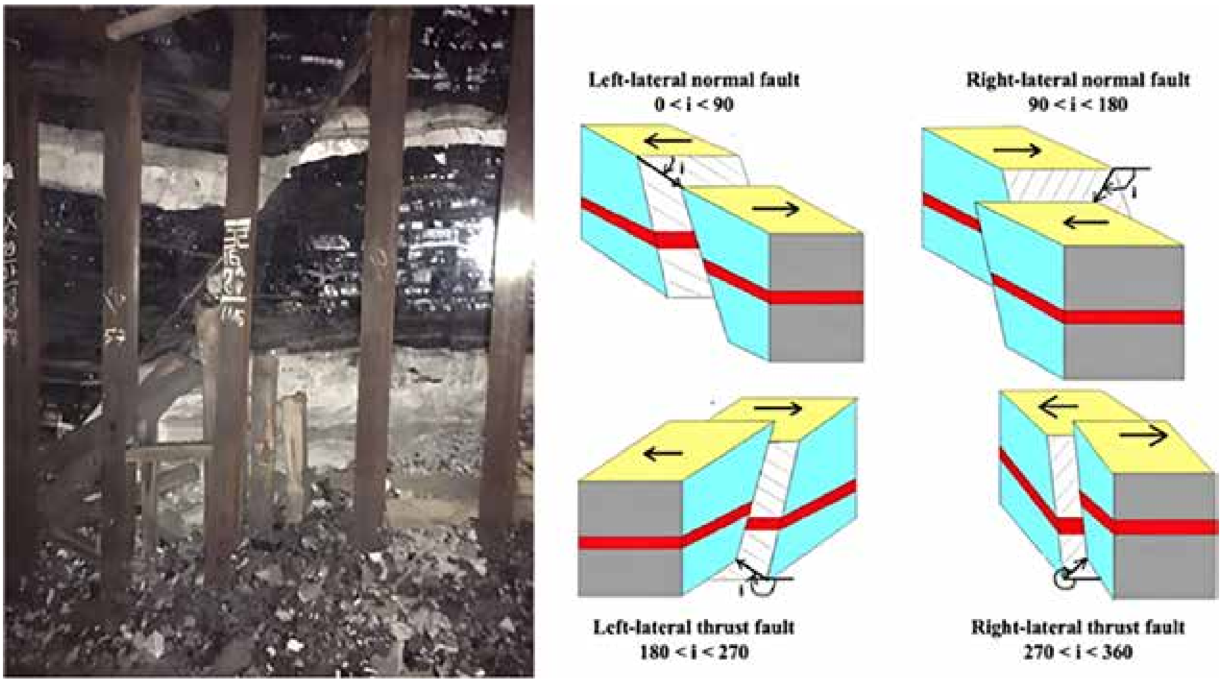


Figure 4: An example of principal in situ stress measurement on a fault and definition and measurement of fault lines.

Deriving Initial Design Outcomes via Empirical Methods

The data obtained from experimental studies, observations, and examinations (**Table 3**) have been utilized to ascertain the design parameters for rock bolts through empirical methodologies. Specific analyses tailored to empirical techniques were conducted to define crucial dimensions such as bolt length (*L*) and bolt spacing (*S*). The summarised outcomes are delineated in **Table 4**.

The determination of the rock bolts' quantity (N) involved separate empirical approaches. After reviewing the N values outlined in **Table 4**, the average N value was computed as 6. However, empirical methods also recommend incorporating shotcrete and/or steel mesh alongside rock bolting to enhance face stability.

In addition to the rock bolting design obtained through empirical approaches, following a comprehensive assessment of field inspections, observations, and engineering experiences, it has been determined that seven rock bolts will be applied for each line. The average values specified in **Table 4**, along with these assessments, have influenced the design outcome shown in **Figure 5**. Additionally, **Figure 5** includes the layout for the coal seam.

As shown in **Figure 5**, the cross-section of the gallery illustrates the utilization of seven rock bolts, featuring a bolt length (L) of 3.3 m, a spacing between bolts (S1) of 1.0 m at the gallery face, and an interval between bolt lines (S2) of 1.0 m along the gallery axis. Based on field observations, measurements, experience, and engineering insights, the plan includes the installation of three roof-anchored rock bolts on the gallery roof in the curved section (P1, M, T1). Likewise, two inclined rock bolts with inclinations of 70° and 50° (T2 and T3, respectively) have been positioned on the pillar (T) side, and on the face (P) side, two inclined rock bolts with inclinations of 70° and 50° (P2 and P3, respectively) have been similarly installed.

Numerical Modelling

The initial design results illustrated in **Figure 5** underwent three-dimensional numerical analyses using FLAC3D v6.0 for the designated A6 panel in this investigation. The analyses conducted include:

Modelling Procedure

During the modelling of the A6 longwall panel in the Ömerler

Table 3: The empirical design utilizes input parameters

Parameter	Symbol	Value
Gallery span (m)	B	4.60
Number of discontinuity sets	n	≥3
Discontinuity dip angle (°)	φ	45°-90°
The average thickness of rock layers on the gallery roof (cm)	t	5
The distance between the discontinuities (m)	Js	0.4
The rock quality value of the coal rock unit in the gallery ceiling	RQD	50
The rock mass quality of the coal rock unit in the gallery ceiling	RMR	32
The thickness of the overlying strata on the gallery span (m)	H	150.25
Unit bulk density of the overlying strata (kN/m3)	γ	21.48
The ratio of horizontal stress (σh) to vertical stress (σv)	K	0.473
The rock quality index of the lignite rock unit in the gallery ceiling	Q	0.37
The height of the rock burden ([(100−RMR)/100]·B) (m)	ht	2.90
The excavation support ratio (1.6-2.0)	ESR	1.80
Equivalent excavation span (B/ESR)	De	2.56
Number of joint sets	Jn	15
Block size	RQD/Jn	50/15 = 3.33

Table 4: Design results for rock bolts derived through empirical methods

Design approach			L	S1	S1 * S2	N
No.	Developer		m	m	m * m	#
1	Panek 1964	(General design results)	2.5	1.0	1.0 * 1.0	4
2	Deere *et al*. 1970	(General design results)	–	0.9	0.9 * 1.0	6
3	Merritt 1972	(General design results)	–	1.2	1.2 * 1.0	6
4	Bieniawski 1973	(General design results)	5.0	1.0	1.0 * 1.0	6
5a	Ünal 1983	(Mechanical rock bolts)	1.90	1.2	1.2 * 1.5	6
5b	Ünal, 1983	(Resin rock bolts)	1.30	1.2	1.2 * 1.5	6
6	Vanketaswarlu 1986	(General design results)	1.80	1.0	1.0 * 1.0	6
7a	Ünal 1986, 1989	(Mechanical rock bolts)	1.98	0.9	0.9 * 1.0	6
7b	Ünal 1986, 1989	(Resin rock bolts)	3.41	0.9	0.9 * 1.0	6
7c	Ünal 1986, 1989	(Swellex rock bolts)	2.89	0.9	0.9 * 1.0	6
8	Barton et al. 1974	(General design results)	–	1.0	1.0 * 1.0	6
9	Grimstad and Barton 1995	(General design results)	1.80	0.9	0.9 * 1.0	6
Overall average			2.5 ± 1	1.0 ± 0.1	1.0 * 1.1	6

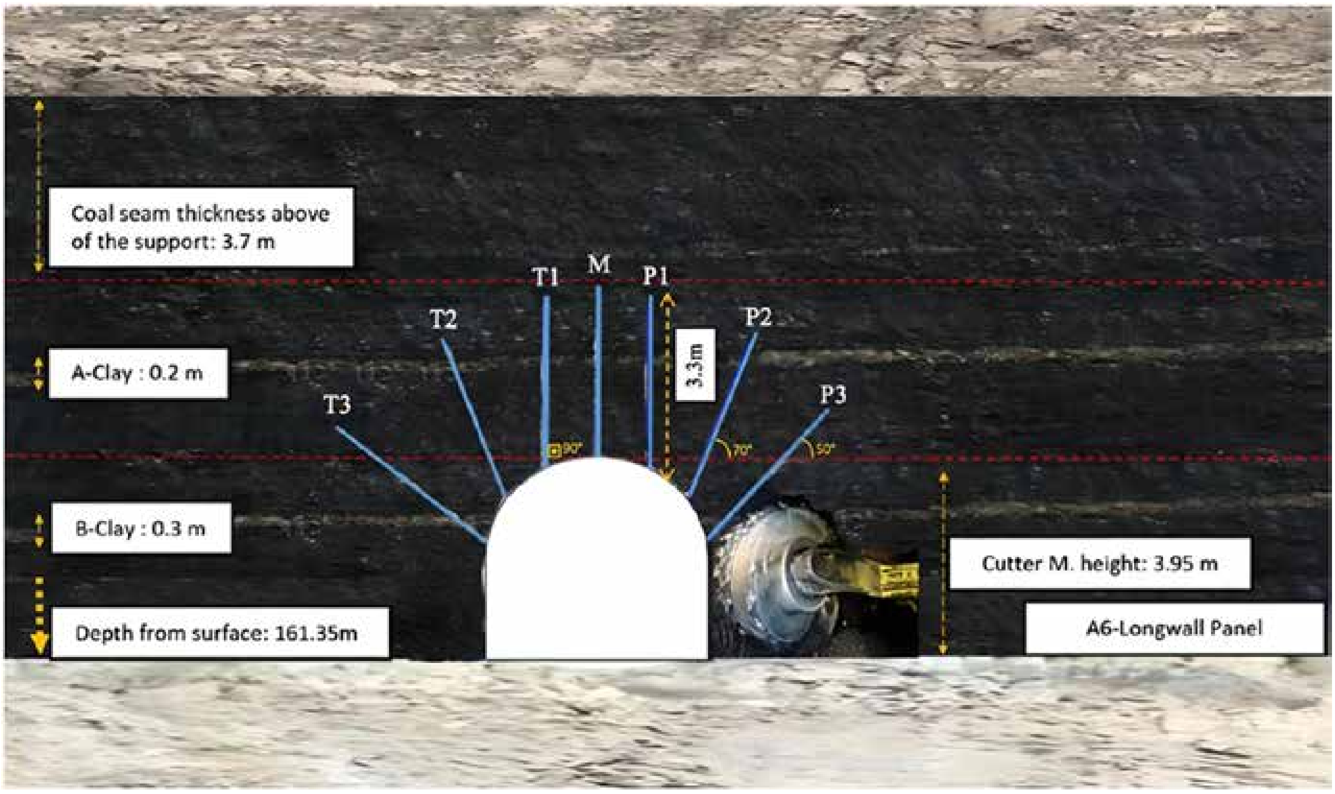


Figure 5: Rock bolt design based on empirical design results.

underground coal mine, the current state of the mine was considered. The solid model incorporates the previously mined and subsided A5 panel, the planned pilot application A6 panel, and the untouched A7 panel on the opposite side of the A6 panel, as depicted in the underground mine map (**Figure 3**). In the model geometry (**Figure 6**), the z-direction signifies depth, the y-direction signifies the length of the longwall panel, and the x-direction represents the length of the longwall face. The model dimensions were defined as + x direction 300 m, −z direction 200 m, and + y direction 500 m.

In the model, the longwall face length in the + x direction is considered to be 90 m with a pillar width of 20 m. In the −z direction, the main strata have a thickness of 11 m, followed by a 140-m claystone unit above the coal seam, 10 m of backfill material above the claystone, and a 39-m claystone unit below the coal seam. The + y direction is defined as 500 m.

To analyse the dynamic effects arising from production in the gallery (longwall panel), it is assumed that the point where the longwall panel eliminates the initial backfill effect is at 450 m. This point is regarded as the starting point of the longwall excavation, implying that the initial 50 m of the panel has been worked and is left as a subsided area (**Figure 6**).

The model geometry utilises rectangular and square-shaped brick elements. The longwall excavation is presumed to be conducted in 1-m-thick slices, and for analysing the dynamic effects it induces, the longwall panel is subdivided into 1-m grids between 450 and 400 m. The remaining sections are further divided into 5-m and 10-m grids. Consequently, the model comprises a total of 361,665 zones and 376,320 nodes (**Figure 6**).

Boundary conditions in a numerical model involve the predetermined values of field variables (such as stress and displacement) set at the grid's boundaries. Boundaries fall into two categories: real and artificial. Real boundaries correspond to features present in the physical object being modelled (e.g., a tunnel surface or the ground surface). Artificial boundaries, although non-existent in reality, must be introduced to enclose the chosen number of zones. For the Ömerler underground coal mine model, roller boundaries are established on the left, right, front, and rear boundaries of the grid, while the bottom of the grid remains fixed. The results from principal stress analyses conducted in situ are incorporated into the model, with an initial condition of K0 = 0.473 (σh /σv) assigned, and the gravitational effect is also defined. In the FLAC 3D program used to create the model for the A6 longwall panel, gob material properties are specified, incorporating equations found in the literature. The mechanical behaviour of the gob is represented by the double-yield model implemented in FLAC 3D.

Pappas and Mark investigated the behaviour of longwall gob material through laboratory tests, concluding that the equation proposed by Salamon in the gob model yielded results closest to laboratory tests. In the Salamon gob model, the following equation is presented (**Equation 1**).

Equation 1

$$\sigma = E0\varepsilon 1 - \varepsilon / \varepsilon m$$

In **Equation 1**, σ represents the uniaxial stress (MPa) on the material, ε denotes the unit deformation of the material under stresses, E0 stands for the initial tangent modulus (MPa), and εm represents the maximum unit deformation possible in the compacted rock material.

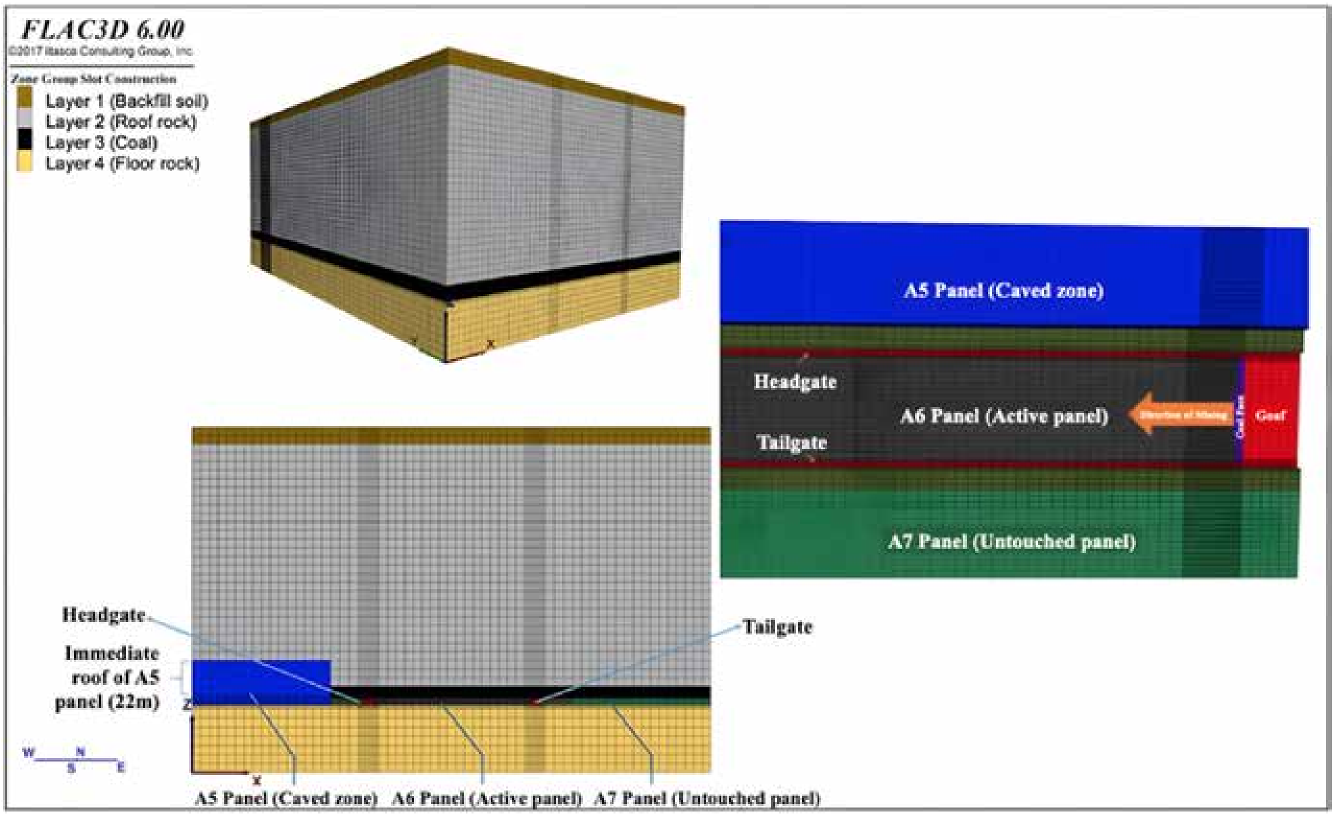


Figure 6: The geometry and details of the model created in FLAC 3D.

Equation 1 was employed in modelling studies to ascertain the mechanical behaviour of the gob. With each 1-m advancement in the face, the A6 panel is associated with a double-yield constitutive model for the 1-m section behind the coal face. Consequently, in the model, during the early stages of face advancement, the gob region represents an area that is broken and collapsed, incapable of withstanding the pressure from the roof. In this region, the gob undergoes slow compression, resulting in increased roof stresses.

For the A6 longwall panel model, the equation governing volumetric unit deformation behaviour, along with deformation change values, is outlined in **Table 5** and expressed in **Equation 2** (**Tables 6, 7**).

Equation 2

$$\sigma=29.2\varepsilon 1-6.25\varepsilon$$

The FLAC 3D utilized beam structural elements to simulate the supports of the A6 longwall panel gates in the Ömerler underground mine, incorporating SAS. These structural elements are characterized by their geometric and material properties within the FLAC 3D program. For the modelling of RBR, pile structural elements were employed in FLAC 3D. In the model, shell structural elements with an elastic modulus (E) of 180 GPa, Poisson's ratio (υ) of 0.3, and a thickness of 45 cm were implemented to represent self-advancing hydraulic roof support units.

Identification and Definition of Monitoring Zones in the Model Geometry

Two separate models have been crafted for three-dimensional analyses. The model reinforced with a steel arch on galleries featuring a horseshoe cross-section is identified as SAS, while the model strengthened with resin-grouted rebar rock bolts is labelled as RBR. In both models, successive activities of preparation (stage 1) and reversible

Table 5: Cap pressure for the double-yield model

Strain (m/m)	Stress (MPa)	Strain (m/m)	Stress (MPa)
0.00	0	0.08	4.67
0.01	0.31	0.09	6.01
0.02	0.67	0.10	7.79
0.03	1.08	0.11	10.28
0.04	1.56	0.12	14.02
0.05	2.12	0.13	20.25
0.06	2.80	0.14	32.70
0.07	3.63	0.15	70.08

Table 6: The input parameters for the SAS in the model

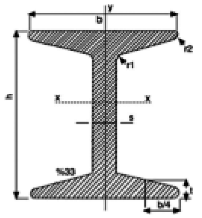
Profile type	GI 140	
Section weight	41.6 kg/m	
Dimensions	*h* = 140 mm – *b* = 110 mm	
Section area	0.0154 m^2	
I_x-I_y	1586-315cm^4	
Density	2701.3 g/m^3	

Table 7: The input parameters for the RBR in the model

Parameter	Value	Source
Rebar diameter (m)	0.020	Mansour Mining product catalogue
Borehole diameter (m)	0.028	Mansour Mining product catalogue
Maximum tensile capacity (kN)	180	Mansour Mining product catalogue
Bolt modulus (GPa)	200	Rocscience, 2007
Tensile strength (MPa)	540	Mansour Mining product catalogue
Boundary axial force (kN)	162	$F = \sigma . A$
Bond strength (N/m)	3.5×10^5	$\tau = P/\pi dl$

production (stage 2) are presumed to occur. To monitor the stresses and deformations produced in the model, a total of 120 monitoring points has been established. In assessing the numerical analysis results, the focus has been given to two station points positioned above the material gallery (headgate) adjacent to panels A5 and A6. These station points are U9 at 300 m and U3 at 429 m along the material gallery (**Figure 7**).

Assumptions and Limitations in the 3D Model

Throughout the modelling process, specific assumptions and constraints were considered. These include:

1. In the model studies, σ_1 is presumed to be vertical (in the −z direction), while σ_2 and σ_3 are considered horizontal (in the x and y directions).

2. The length of the A6 longwall panel, originally spanning between 400 and 450 m, was approximated as 500 m in the y direction within the model.

3. To define the shield support units in the model, were represented using shell structural elements, the SAS with beam structural elements, and the RBR with pile structural elements.

4. The dip angle of the coal seam where the A6 longwall panel is situated was assumed to be 0° in the model. Additionally, groundwater was disregarded in the modelling studies, as excavation works are conducted above the underground water table.

Pilot Application and Monitoring Studies

At the TKI-GLI Ömerler underground coal mine, pilot application and monitoring studies to performance analysis of the two different support system have been carried out. In the coal mine, a 45-m section located at the headgate of the A6 panel has been designated as a pilot area for testing and monitoring (**Figure 8**). The commonly used SAS method in the mine has been employed as support in the initial 20-m section of this area. Convergence measurement stations (CO) have been established at three points to monitor displacements associated with coal production in the SAS zone.

Following the completion of the SAS zone, a rock bolting design specified in **Figure 5** has been implemented for the RBR support system in the 25-m section. To address potential safety issues arising from the RBR application in this 25-m zone, previously existing steel arches have been loosened and put into a passive state. Convergence measurement stations (CO) have been established at five points in the RBR zone to monitor displacements associated with coal production (**Figure 8**).

During the RBR application, after scanning the roof, three rock bolts (P1, M, T1) were initially placed in the roof. Subsequently, angled rock bolts (P2, P3, T2, T3) were installed on both sides of the gallery at angles of 50° and 70°. The rock bolt length (L) and spacing (S) were taken as 3.3 m and 1 m, respectively, based on the design detailed in **Figure 5** (**Figure 9**). Holes for rock bolts were drilled using a drilling machine with a 28-mm drill bit. Four resin cartridges with a diameter of 23 mm and a length of 60 cm were placed in each hole. The solidification time for the used resins is 180 s.

For the performance evaluation of the support systems in the pilot application area, monitoring systems have been implemented in both the 20-m SAS zone and the 25-m RBR zone. In each of these zones, sections equipped with convergence (CO) measurement stations at approximately 5-m intervals have been established (**Figure 8**). Every shift, one measurement was taken, and measurements continued until the 45-m area was traversed and remained beneath the caving zone due to the in-seam production activities Measurements were continuously collected from these stations over time and in conjunction with the progress of the longwall excavation.

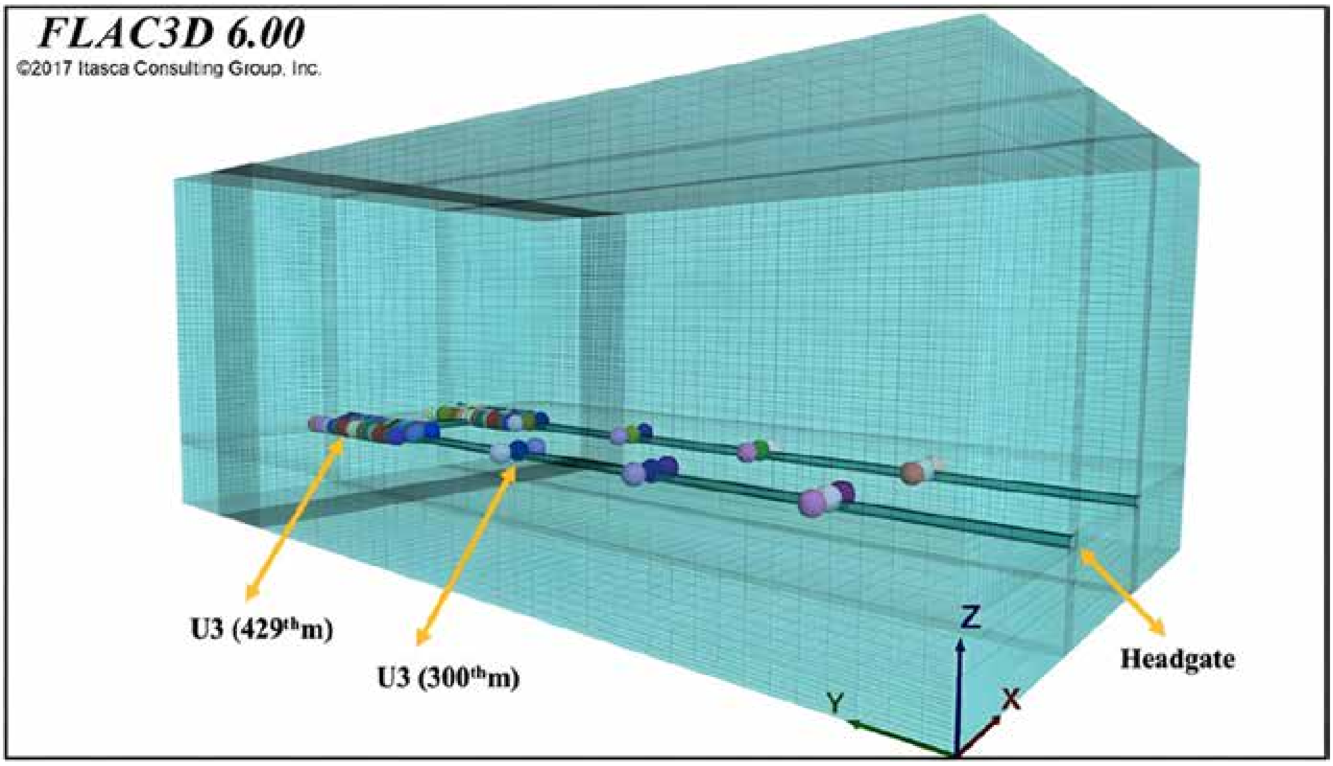


Figure 7: Placement of the monitoring points in the numerical model.

RESULTS AND DISCUSSIONS

Numerical Modelling Results

The A6 panel, defined as a longwall panel with a headgate length of 500 m, was separately modelled for the SAS and RBR support systems. Each numerical model was run in two separate stages. In the first stage (stage 1), excavation and reinforcement of the gate roads for the A6 panel were performed. In the second stage (stage 2), the goaf behind the supports in the A6 panel was caved, the longwall face was prepared, and coal production was carried out at 1-m intervals. The results of these two stages for both models were evaluated separately for the monitoring zone at the 300th meter of the headgate in the A6 panel (U9) and the monitoring point at the 429th meter (U3). Consequently, vertical displacements and changes in vertical secondary stresses were recorded at monitoring points U3 and U9, and the performances of SAS and RBR were assessed. **Figure 10** presents the graphical representation of vertical displacement and changes in vertical secondary stresses for the SAS reinforcement model in stage 1. The data obtained from these graphs are specified in **Table 8**.

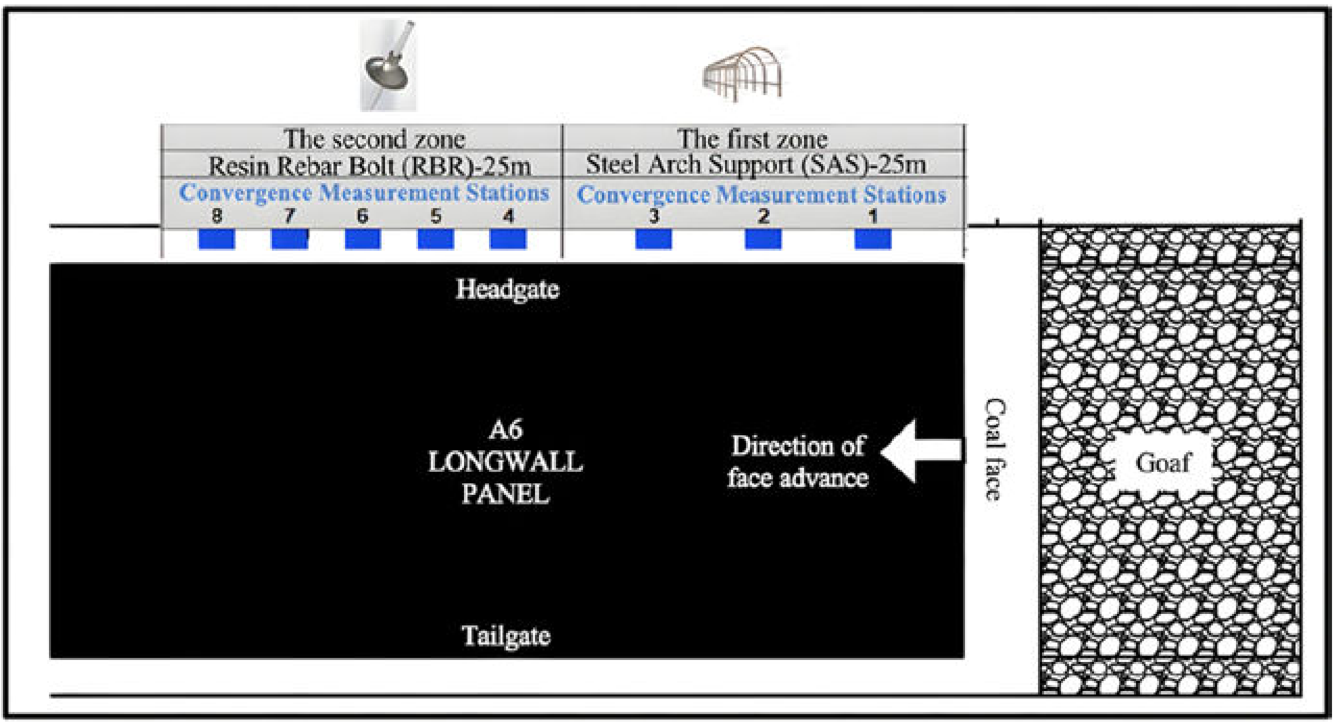


Figure 8: The application zones in the headgate and the number of CO stations in the A6 panel.

Figure 9: Typical images of the stages of RBR installation

The data in **Table 8** and **Figure 10** show that vertical displacements and vertical secondary stresses remain very low in the first 200 m as the excavation face approaches the monitoring point located at the 300th meter of the headgate, denoted as U9. Even with 100 m remaining to reach the U9, the values appear to stay close to the initial primary values in the field. However, as the excavation face approaches the U9 at the 300th meter, vertical displacements and secondary stresses start to change rapidly, and when the excavation face reaches the U9, these values are $U=57$ mm and $P=-40$ kPa. After the excavation face passes the U9, vertical displacement continues to change rapidly up to the 400th meter. As the excavation face reaches from the 400th to the 500th meter in the gallery, it is understood that the vertical displacement values at the remaining U9 in the gallery change very little, reaching $U=96.2$ mm. Similarly, it is understood that the vertical stress values undergo very little change up to the 500th meter after the excavation face passes the U9. When the excavation face reaches the 500th meter in the gallery, it is observed that the vertical stress values at the remaining U9 point in the gallery remain almost constant, reaching $P=-10$ kPa.

The vertical displacement and secondary stress values at the U3 monitoring point located at 429 m on the A6 longwall panel (**Figure 7**) were determined using FLAC 3D. The model outputs showing the vertical displacement and secondary stress values at the U3 during the period from the start of excavation in the longwall face to the 18th meter of the advancing excavation face in the completed preparation panel (stage 2) are presented in **Figure 11**. The vertical displacement and secondary stress values observed in the model outputs are presented in **Table 9**.

Table 9 and **Figure 11** illustrate the longwall advancement at 1-m intervals in the model. The monitored U3 point is located at the 429th meter of the headgate, initially positioned 18 m behind the excavation face. As excavation progresses in the longwall face, displacements, and stresses at the U3 monitoring point begin to change. While displacements are relatively minor within the first 10 m, they rapidly escalate within the final 8 m (**Figure 11**). Upon the longwall excavation advancing 18 m and reaching the U3 monitoring point, the total displacement amounts to $U=376$ mm. Initially characterized by tensile stresses, stress variations subsequently transition to compressive stresses. Upon complete advancement of the longwall excavation to the U3 monitoring point, the stress value in the gallery roof amounts to $P=-1.8$ kPa.

Similar to the SAS support model, the gate roads of the A6 longwall panel were modelled using the RBR support system. Vertical displacement and secondary stress results

Table 8: Vertical displacements and vertical secondary stress values of U9 for stage 1 (SAS**)**

Gallery excavation	Monitoring point U9	Monitoring point U9
***L* (m)**	***U* (mm)**	***P* (kPa)**
0	−6.5*	−3370.00*
50	−6.5	−3367.50
100	−6.5	−3365.00
150	−6.5	−3362.50
200	−6.5	−3360.00
250	−30	−1600.00
300**	−57	−40.00
350	−76.6	−30.00
400	−96.2	−20.00
450	−96.2	−15.00
500	−96.2	−10.00

*The amount of vertical displacement and secondary stress resulting from initial conditions, in monitoring point U9

**U9 monitoring point is located at the 300th meter of excavation

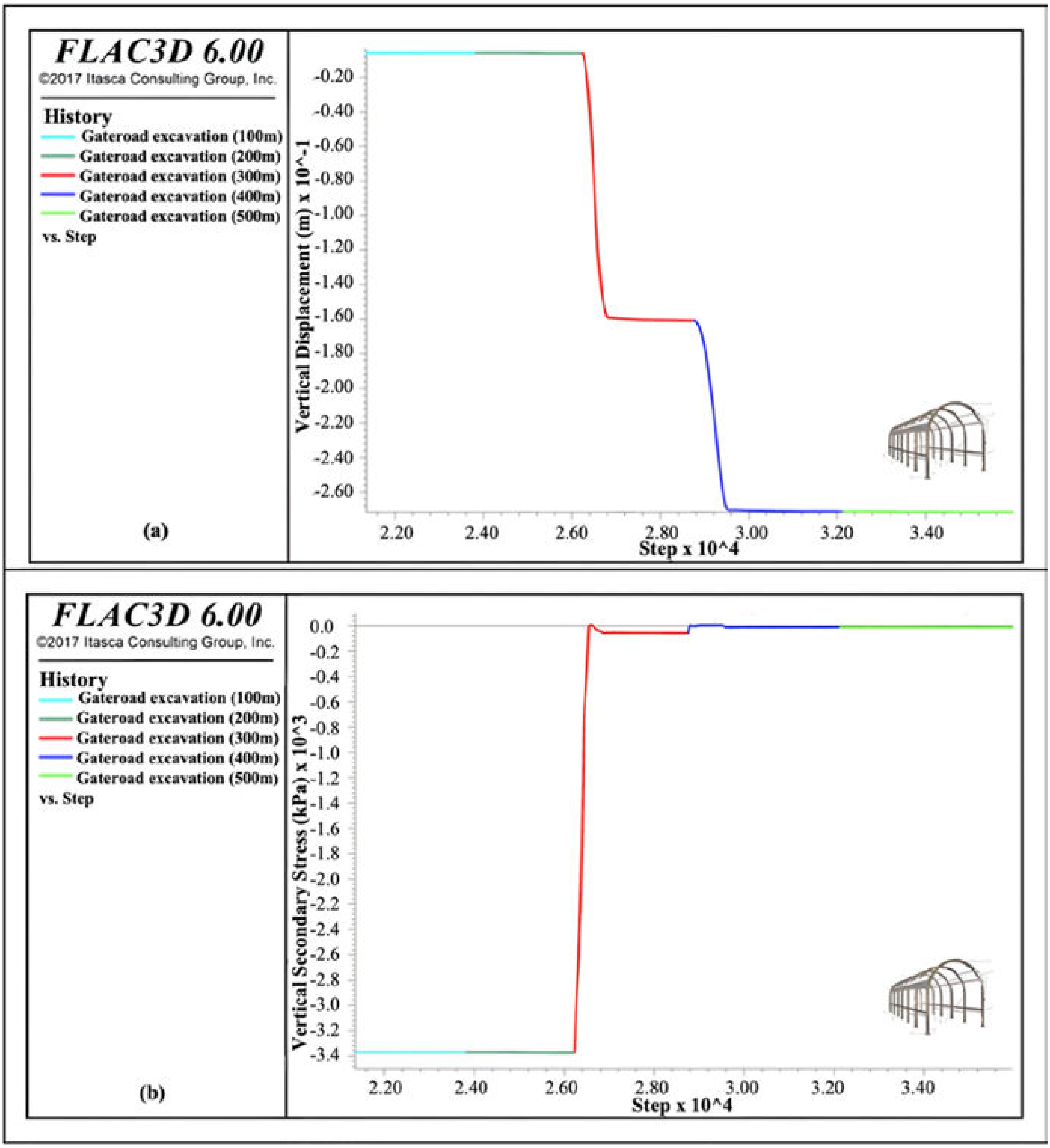


Figure 10: (a) Vertical displacements and (b) vertical secondary stresses in the gallery roof at the 300th m of the headgate (monitoring point U9), during gate road excavation and SAS reinforcement in the A6 panel (Stage-1).

at the monitoring point labelled U9 are presented in **Figure 12** and **Table 10**.

Table 10 and **Figure 12** reveal that within the initial 200 m, vertical displacement and secondary stress values remain relatively low as the excavation face progresses towards the monitoring point at the 300th meter of the headgate, identified as U9. Even with only 100 m left to reach U9, these values stay close to their initial measurements. However, as the excavation face nears U9, both vertical displacements and secondary stresses start to rise rapidly. Upon reaching U9, these values reach $U = 14.7$ mm and $P = -3463$ kPa. Beyond U9, vertical displacement continues to fluctuate rapidly until the 400th meter. From the 400th to the 500th meter, minimal changes are observed in vertical displacement at the remaining U9, stabilizing at $U = 26.4$ mm. Similarly, vertical stress values decrease rapidly until the 400th meter after surpassing U9, then stabilize until the 500th meter. At the 500th meter, vertical stress values at the remaining U9 remain almost constant, reaching $P = -3344$ kPa (**Table 10; Figure 12**).

The vertical displacement and secondary stress results at the monitoring point labelled U3, up to the 18th excavation of the 1-m coal face (stage 2), for the RBR support model are presented in **Figure 13** and **Table 11**.

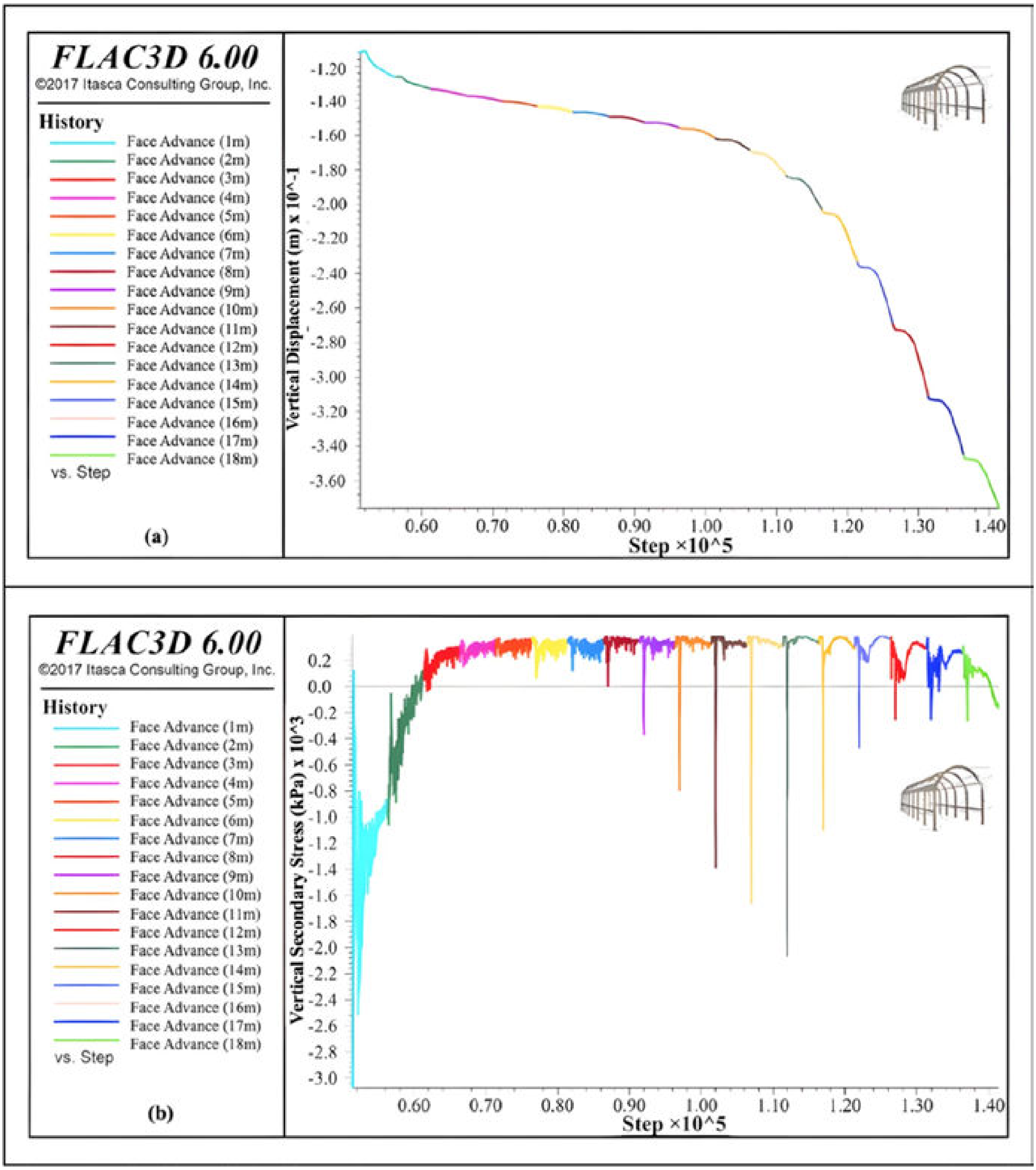


Figure 11: (a) Vertical displacements and **(b)** vertical secondary stresses in the gallery roof at the 429th m of the headgate (monitoring point U3), during gate road excavation and SAS reinforcement in the A6 panel (Stage-2).

As seen in **Table 11** and **Figure 13**, the longwall advancement in the model was executed at 1-m intervals. The monitored U3 point is located at the 429th meter of the gate road. This point is initially positioned 18 m behind the excavation face. As excavation progresses in the longwall face, displacements, and stresses at the U3 monitoring point begin to change. Displacement values, which initiate within the first 10 m, rapidly escalate within the final 8 m (**Figure 13**). Upon the longwall excavation advancing 18 m and reaching the U3 monitoring point, the total displacement amounts to $U = 106$ mm. While stress variations remain nearly constant up to the last 8 m, they subsequently decrease rapidly, culminating at a stress value of $P = -1840$ kPa when the excavation face reaches the U3 monitoring point (**Table 11**; **Figure 13**).

In Situ Measurement Results

Continuous convergence measurements were taken from CO stations set up in the field to determine the performance of the existing SAS reinforcement in the 20-m zone in front of the coal face where production takes place and the subsequent 25-m zone where RBR is applied [12]. In the

Table 9: Vertical displacements and vertical secondary stress values of U3 for stage 2 (SAS)

Longwall coal face advancement	Monitoring point U3	Monitoring point U3
L (m)	*U* (mm)	*P* (kPa)
0	−112.000	−30.800
1	−126.000	8.800
2	−132.000	2.800
3	−138.000	1.400
4	−140.000	0.800
5	−143.000	0.800
6	−145.000	0.800
7	−148.000	0.800
8	−152.000	0.700
9	−156.000	0.700
10	−162.000	0.700
11	−168.000	0.700
12	−184.000	0.700
13	−204.000	0.600
14	−238.000	1.200
15	−262.000	0.400
16	−312.000	1.200
17	−348.000	1.600
18	−376.000	−1.800

Table 10: Vertical displacements and vertical secondary stress values of U9 for stage 1 (RBR)

Gallery Excavation	Monitoring point U9	Monitoring point U9
L (m)	*U* (mm)	*P* (kPa)
0	−7.1*	−3405.00**
50	−7.15	−3406.50
100	−7.205	−3408.00
150	−7.3	−3410.00
200	−7.4	−3412.00
250	−10.8	−3428.00
300**	−14.7	−3463.00
350	−20	−3404.00
400	−25.9	−3347.00
450	−26	−3345.00
500	−26.4	−3344.00

*The amount of vertical displacement and secondary stress resulting from initial conditions, in monitoring point U9
**U9 monitoring point is located at the 300th meter of excavation

first 20-m section with SAS located just ahead of the coal excavation face, measurements were taken from three CO (CO-1, CO-2, and CO-3) stations, while in the following 25-m section with RBR, measurements were taken from five CO measurement stations (CO-4, CO-5, CO-6, CO-7, and CO-8). The measurement results obtained over time are presented in **Figure 14**, and those related to the distance from the coal face are depicted in **Figure 15**.

As depicted in Figure 14, the blue curves representing the SAS zone have experienced faster and larger deformations compared to the red curves representing the RBR zone. Convergence values in the SAS zone ranged from 234.46 to 391.60 mm, while in the RBR zone, they ranged from 105.78 to 203.94 mm. Due to the distance of 10 m between the last station CO-3 within the SAS zone and the starting point of the RBR zone, it is considered that the RBR zone affects this point within the SAS zone, resulting in convergence values measured at the CO-3 station to be lower than those at CO-1 and CO-2 stations.

Figure 15 considers the progress distances in the coal face. As depicted in the presented graph, in the SAS-zone (blue curves), convergence values reach 391.602 mm at the CO-1 station, which is closest to the excavation face. Similarly, in the RBR zone, the convergence value measured at the CO-4 station, closest to the excavation face, is 203.94 mm. As the excavation face progresses in

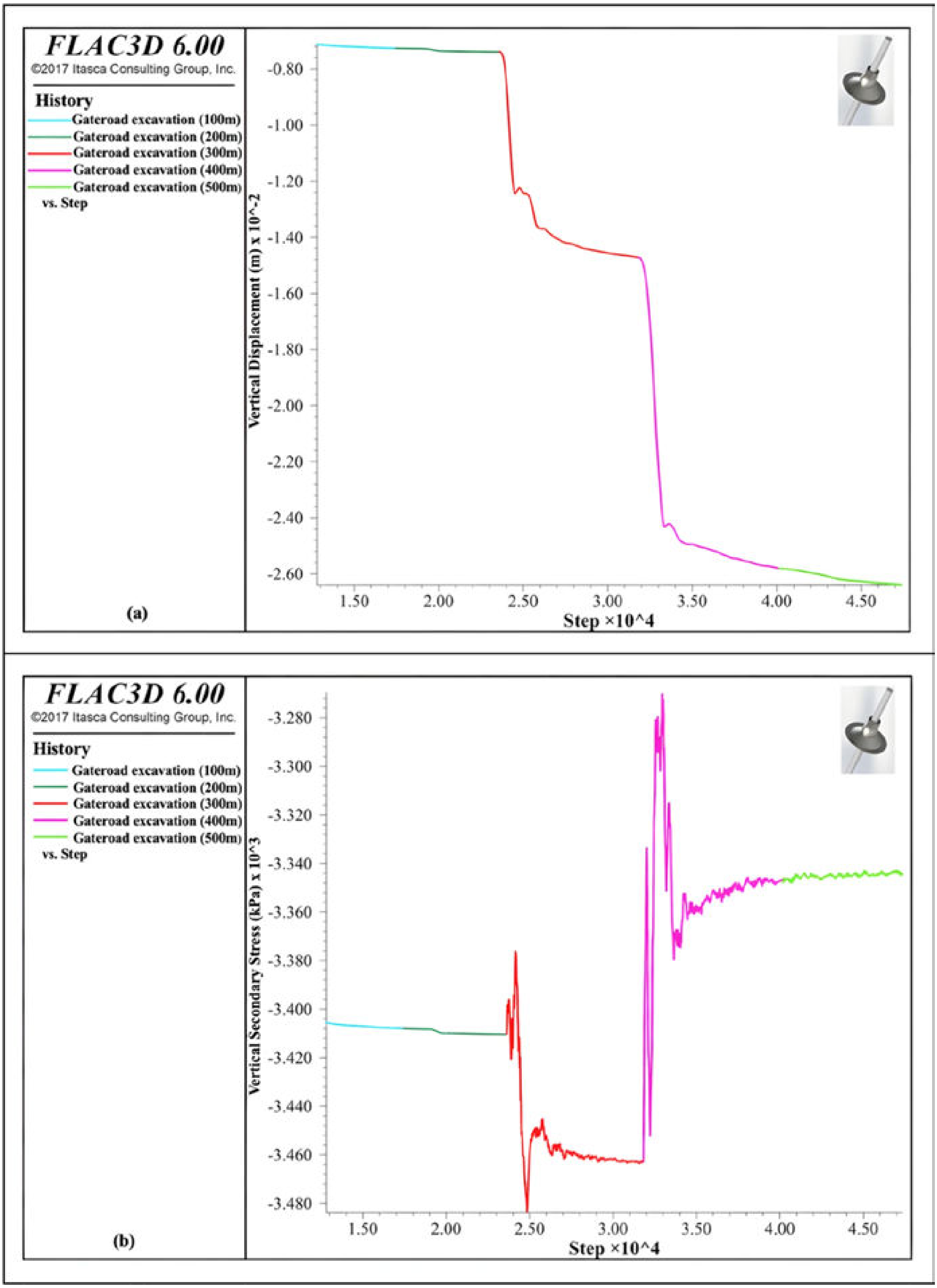


Figure 12: (a) Vertical displacements and **(b)** vertical secondary stresses in the gallery roof at the 300th m of the headgate (monitoring point U9), during gate road excavation and RBR reinforcement in the A6 panel (Stage-1).

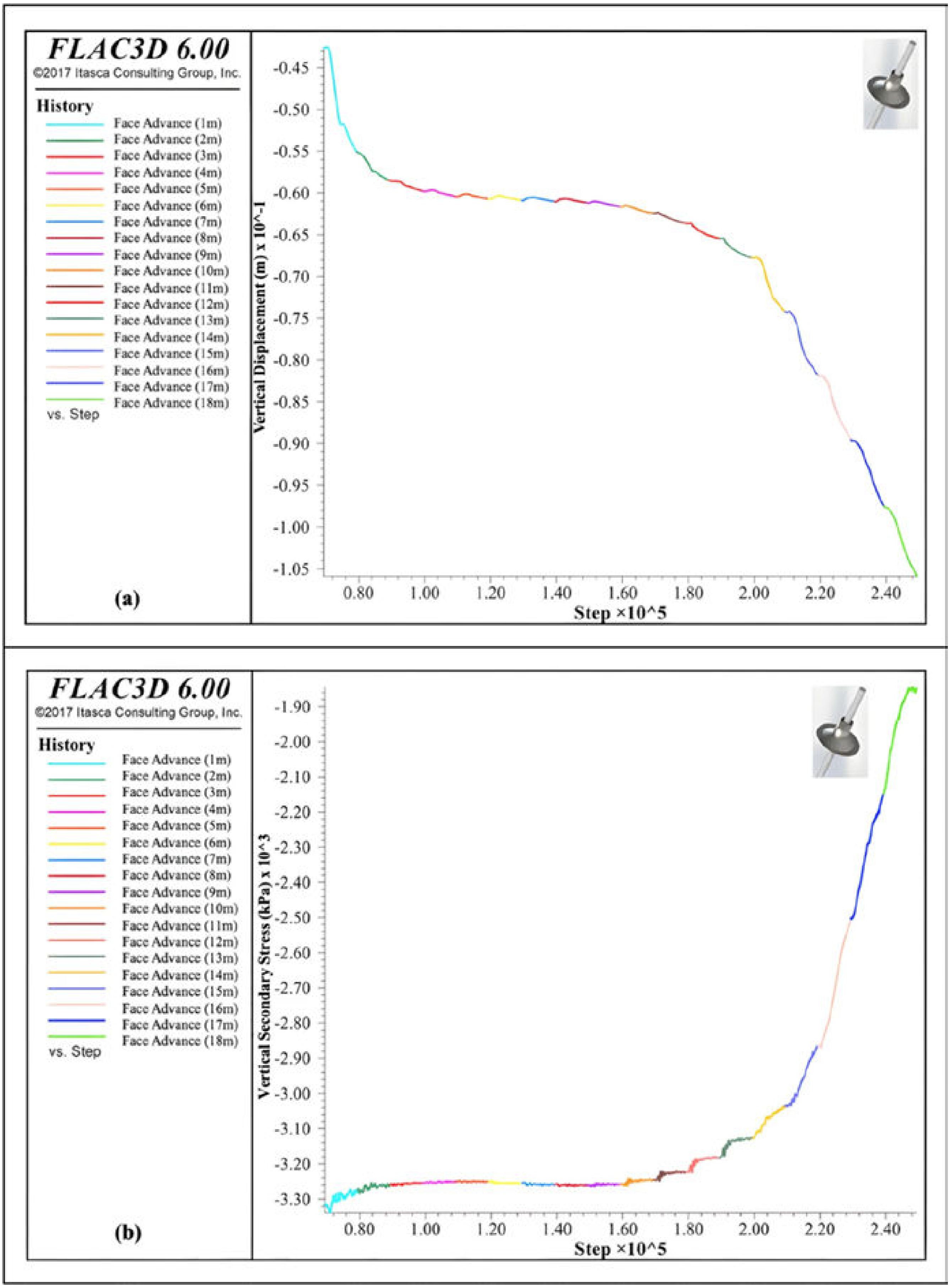


Figure 13: (a) Vertical displacements and **(b)** vertical secondary stresses in the gallery roof at the 429th m of the headgate (monitoring point U3), during gate road excavation and RBR reinforcement in the A6 panel (Stage-2).

Table 11: Vertical displacements and vertical secondary stress values of U3 for stage 2 (RBR)

Longwall coal face advancement	Monitoring point U3	Monitoring point U3
L (m)	*U* (mm)	*P* (kPa)
0	−43.000	−3320.000
1	−55.000	−3270.000
2	−58.500	−3260.000
3	−60.000	−3250.000
4	−60.050	−3250.000
5	−60.100	−3250.000
6	−60.100	−3260.000
7	−60.100	−3260.000
8	−60.100	−3260.000
9	−60.200	−3250.000
10	−62.500	−3240.000
11	−63.000	−3220.000
12	−65.000	−3180.000
13	−67.000	−3140.000
14	−74.000	−3040.000
15	−81.000	−2880.000
16	−89.000	−2520.000
17	−97.000	−2160.000
18	−106.000	−1840.000

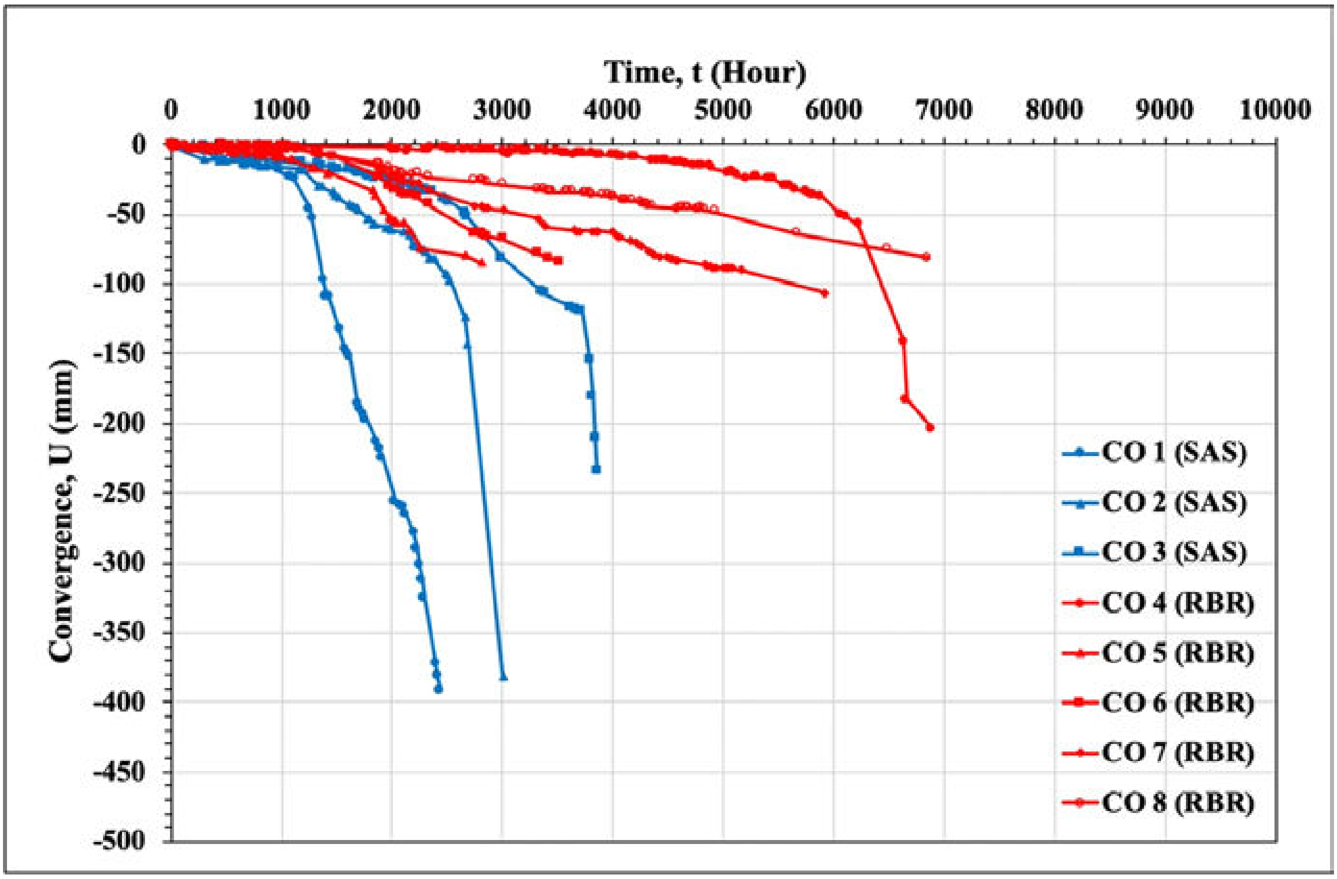


Figure 14: Time-dependent convergence curves obtained in the SAS and RBR zones of the A6 headgate.

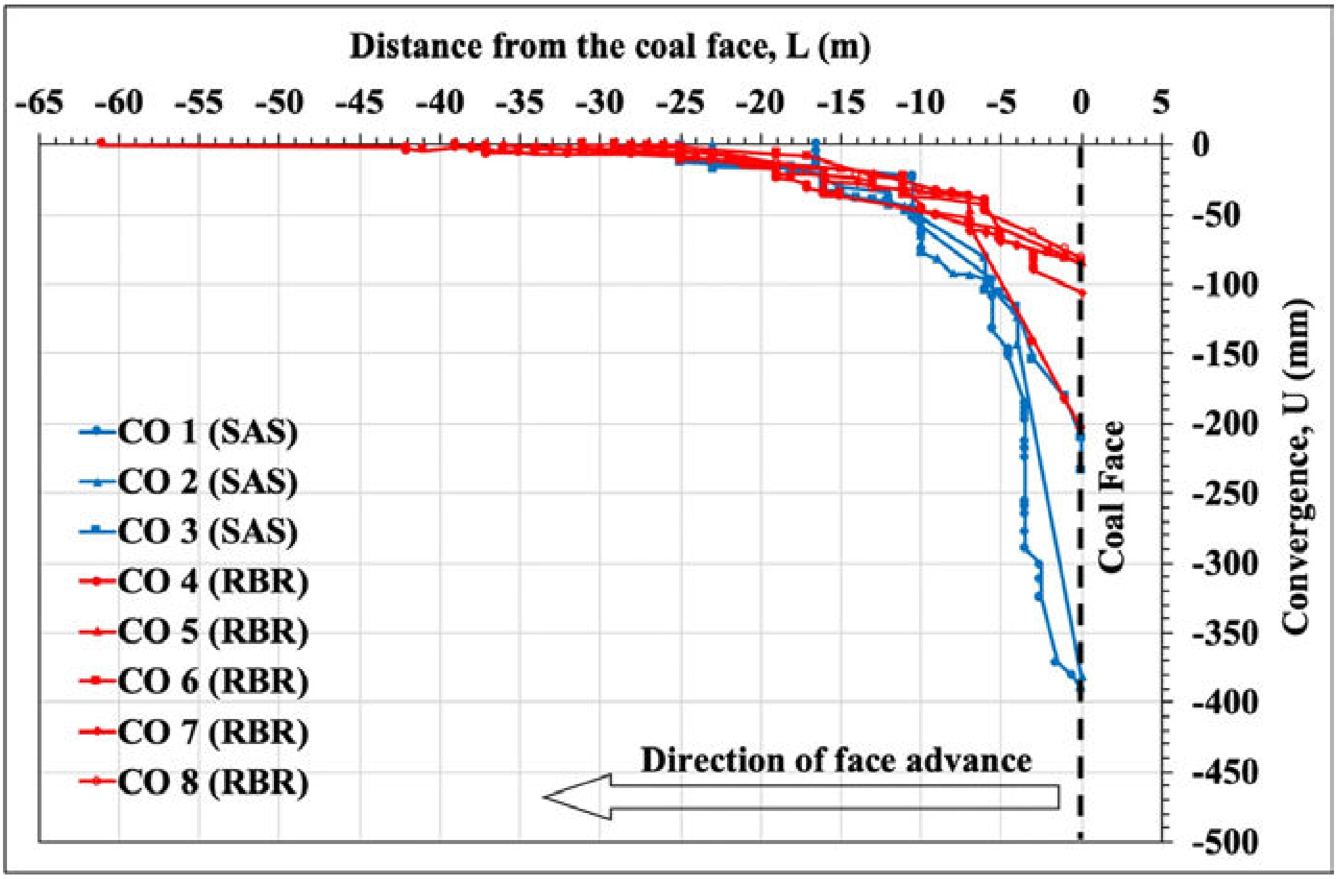


Figure 15: Convergence curves as a function of distance from the coal face obtained in the SAS and RBR zones of the A6 headgate.

the RBR zone, the convergence values read at the other CO-5, CO-6, CO-7, and CO-8 stations in this zone reach a maximum of 105.78 mm. This situation is related to the liberation of the gallery roof from the influence of the SAS zone.

When considering the maximum displacement values observed under the same conditions for both zones, it is determined that the RBR-reinforced zone performs its duty of supporting the roof during coal production activities 52% more successfully than the SAS-reinforced zone.

Numerical Modelling and In Situ Measurement Results Evaluation

In this section, the numerical modelling results and in situ measurement results of vertical displacement values associated with the advancement of the coal face have been compared on the same graph for SAS and RBR support systems (**Figure 16**). Vertical displacement values from the numerical models created for SAS and RBR support systems were compared with convergence measurement results obtained in the field at the CO-2 station located in the middle of the SAS zone and the CO-6 station located in the middle of the RBR zone, relative to the monitored U3 observation point. These results are presented on the same graph in **Figure 16**.

As seen in **Figure 16**, according to the numerical model results, a vertical displacement of 250 mm occurred in the roof over the 18-m advancement of the coal face for the SAS, while the in situ measurements indicate this value to be 363.76 mm. For the RBR, the numerical model results predict a vertical displacement of 51 mm over the 18-m advancement of the coal face, whereas the in-situ measurements show this value to be 76.36 mm. Consequently, **Figure 16** reveals that both the numerical model results and the in situ measurement results indicate that the RBR reinforcement system performs its support function more effectively during the advancement of the coal face compared to the SAS reinforcement system.

In **Figure 16**, differences between the vertical displacement results obtained from numerical analysis and in situ measurements are observed in both RBR and SAS systems. These differences are due to the local complex geological conditions of the measurement area and the unsystematic nature of mining activities. In other words, these differences are associated with problems hindering the systematic progress of mining activities in the A6 panel. While activities such as reinforcement design are systematically conducted in numerical analyses, real-world mining schedules are not always executed as planned due to issues like belt malfunctions, ventilation problems, and equipment breakdowns. Predicting and integrating such unforeseen circumstances into numerical models, especially in underground mining activities, is quite challenging. A similar situation holds for the Ömerler coal mine site discussed in this study. Therefore, the differences observed between the numerical analysis outputs and the actual measurement results in Figure 16 can be attributed to irregular delays caused by unwanted issues in mining activities. In conclusion, the comparison presented in Figure 16 demonstrates that the RBR system provides more effective support during the advancement

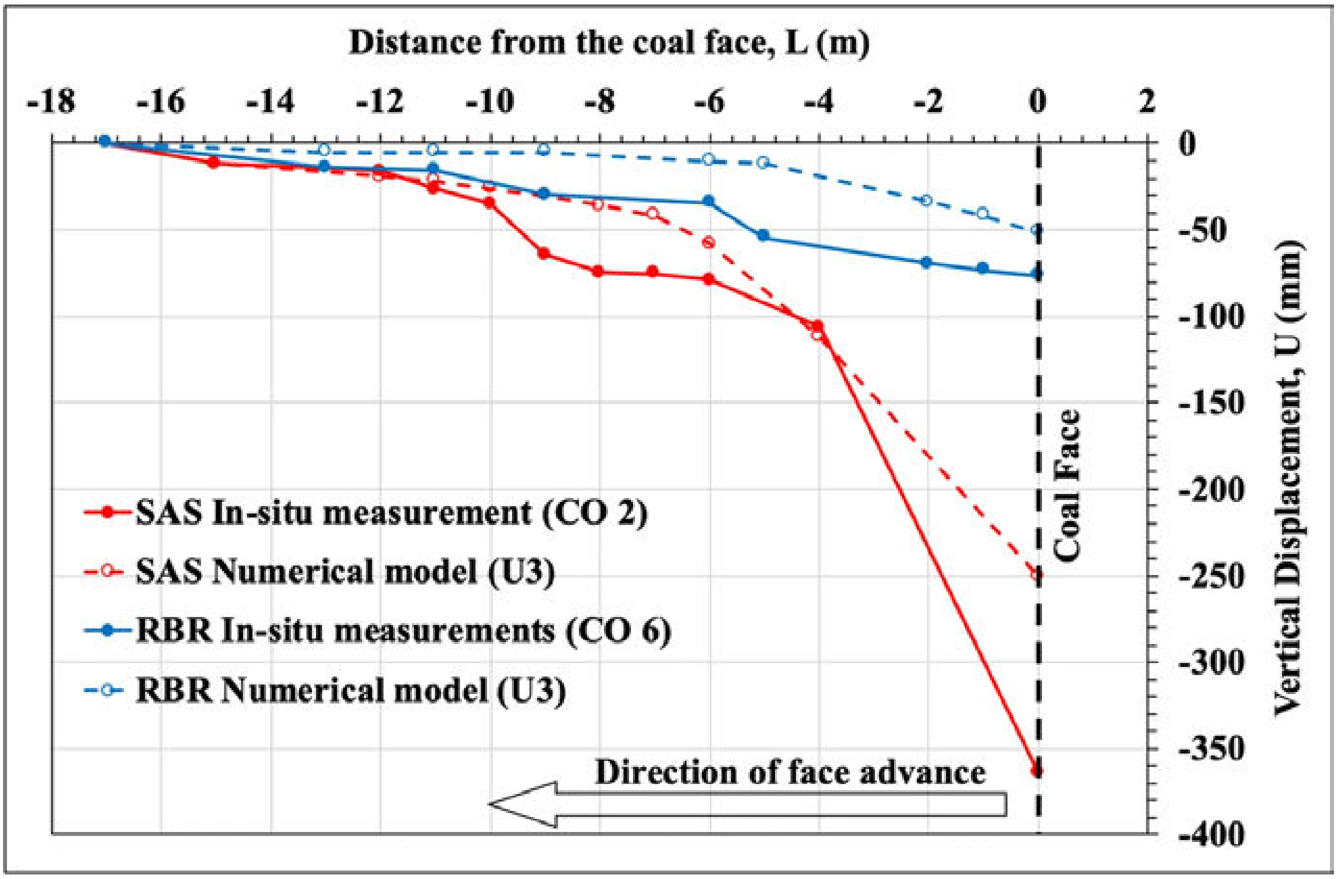


Figure 16: Comparison of numerical modelling and in situ measurement results for vertical displacement values due to 18-m coal excavation for SAS and RBR

of the coal face compared to the SAS system. This finding is supported by both the numerical model results and the in-situ measurements.

CONCLUSIONS

In this study, the feasibility of rock bolting support in an underground coal mine gallery with a thick coal seam has been investigated through numerical modelling. In this context, the Ömerler underground coal mine area, belonging to the TKI-GLI which is located in the Tavşanlı district of Kütahya province, was selected as the study area. Rock mass and rock material properties were determined through in situ and laboratory studies conducted in the mine, and experimental, empirical, and numerical analyses were performed based on the obtained data. Numerical modelling was conducted using FLAC3D v6.0 finite difference method modelling software.

According to the design results obtained, the RBR and SAS were implemented in the pilot application area. In situ monitoring studies were carried out to evaluate the performance of the RBR and SAS systems in this pilot application area.

The results of the numerical modelling indicated that there were less displacement and less secondary stress change in the RBR-supported area compared to the SAS-supported area. Additionally, in situ measurements showed that the RBR more successfully supported the roof during coal production activities. It was determined that the RBR supported the roof 52% more effectively compared to the SAS.

These findings demonstrate that when evaluating the applicability of rock bolting support systems in underground galleries with thick coal seams in the Ömerler underground coal mine, the RBR system is a more effective solution. This study emphasizes the importance of more sustainable and secure support systems to enhance operational efficiency in the coal mining industry.

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Below is a sample of references, for further reading please use the link provided.

Evaluation and Comparison of Rock Bolting Versus Steel Arch Support Systems in Thick Coal Seam Underground Galleries: A Case Study | Mining, Metallurgy & Exploration

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Research and practice of intelligent coal mine technology systems in China

This article considered the role of coal as China's basic energy source and examines the development of the coal industry. We focused on the intelligent development of coal mines and introduced the "Chinese mode" of intelligent mining in underground coal mines, which uses complete sets of technical equipment to propose classification and grading standards. In view of the basic characteristics and technical requirements of intelligent coal mine systems, we established a digital logic model and propose an information entity and knowledge map construction method. This involves an active information push strategy based on a knowledge demand model and an intelligent portfolio modelling and distribution method for collaborative control of coal mines. The top-level architecture of 5G+ intelligent coal mine systems combines intelligent applications such as autonomous intelligent mining, human-machine collaborative rapid tunnelling, unmanned auxiliary transportation, closed-loop safety control, lean collaborative operation, and intelligent ecology. Progress in intelligent mining technology was described in terms of a dynamic modified geological model, underground 5G network and positioning technology, intelligent control of the mining height and straightness of the longwall working face, and intelligent mining equipment. The development of intelligent coal mines was analysed in terms of its imbalances, bottlenecks, and the compatibility of large-scale systems. Implementation ideas for promoting the development of intelligent coal mines were proposed, such as establishing construction standards and technical specifications, implementing classification and grading standards according to mining policy, accelerating key technology research, and building a new management and control model.

Over the past 40 years, China's coal industry has achieved significant progress through comprehensive mechanization. From 2016 to 2019, the long-term safety production mechanisms were improved, coal mine mechanization, automation, and intelligence were accelerated, and the efficiency and safety levels were comprehensively enhanced. The withdrawal of outdated coal production capacity is currently running at over 900 million t/a, which significantly reduces the environmental footprint of the coal industry. At present, there are more than 3000 coal mines in China, including more than 1000 large-scale coal mines with an annual output of more than 1.2 million tons.

In 2020, the national raw coal output was 3.84 billion tons, and the total coal consumption was nearly 4.14 billion tons. Coal accounts for 55.3% of primary energy production and 56.8% of primary energy consumption. China is not yet fully industrialized, and so the level of urbanization will continue to increase, and the level of electrification still has great room for improvement . China has a huge demand for energy consumption. In 2019, China's per capita primary energy consumption was 3.47 tons of standard coal per year, which is far lower than that of the United States, Canada, and other developed countries (the OECD per capita average is about 6 tons of standard coal per year, while Canada, the United States, Australia, and other developed countries have a per capita energy consumption of about 10 tons of standard coal per year). The development of China's economy requires strong support from energy, and so China's energy demand is likely to grow, with coal remaining the main energy source for some time to come.

Given the coal resources in China, underground mining is the main method of extraction, with open-pit mining accounting for less than 15% of coal production. Scientific research has enabled underground mining to shift from mechanized mining to automated and intelligent mining. Coal mine intelligence is the core technical support for the high-quality development of the coal industry in this new development stage and has become the industry consensus. In recent years, the research and development of intelligent coal mine technology systems have achieved significant progress. Currently, 71 intelligent coal mines are in construction, and the development of intelligent coal mines is accelerating.

OVERVIEW OF INTELLIGENT COAL MINE DEVELOPMENT IN CHINA

Transformation and development from mechanization to intelligence

The coal seams in China are complex and diverse. In the last century, artificial mining and blasting mining were used for a long time, resulting in low efficiency and high casualty rates. In the mid-1980s, fully mechanized mining equipment for the medium-thick coal seams was introduced to carry out longwall comprehensive mechanized mining. However, the incompatibility of the hydraulic supports required for fully mechanized mining with the complex and changeable coal seam conditions in China led to the hydraulic supports often being crushed at the working face. In view of the problems encountered in longwall fully mechanised mining, systematic research and development has focused on the theory, technology, and equipment of fully mechanised mining, leading to a complete set of technologies and equipment for fully mechanised mining in thin and medium-thick coal seams, at large mining heights, and for caving mining.

In the past 10 years, innovative research and development on intelligent mining technology and equipment have seen breakthroughs in a number of key core technologies and important achievements in intelligent fully mechanized mining of thin and very-thin coal seams, at large and super-large mining heights, and in the equipment required for extra-thick coal seams. Some mines in Huangling, Shaanbei, Shandong, and other mining areas have achieved varying levels of automation, resulting in intelligent unmanned mining of thin coal seams (less than 1.3 m) and intelligent fully mechanized mining at super-large mining heights of 6-9 m. This provides a solid foundation for comprehensively promoting the intelligent development of coal mines.

The rapid development of modern information and control technology has modified many traditional industries and promoted changes in human lifestyles, forcing the mining industry to move away from traditional high-intensity work methods. Intelligent mining pioneers and pilot companies enjoy cost and development advantages. At the same time, the recruitment difficulties faced by coal mining companies have forced coal mines to transform from comprehensive mechanization to intelligent development and accelerate the construction of intelligent coal mines. Intelligent coal mines are characterized by deep integration of the Internet of Things (IoT), cloud computing, big data, artificial intelligence, automatic control, mobile internet technology, and intelligent equipment with coal development technology to enable comprehensive autonomous perception, real-time and efficient interconnection, intelligent analysis and decision-making, independent learning, dynamic prediction and early warning, and accurate collaborative control. The result is efficient and intelligent operation across the whole process of mine geological protection, coal mining, production, and operation management. The fundamental goal of developing intelligent coal mines is to increase safety, improve efficiency, increase the recovery rate of resources, and achieve high-quality development of coal mines .

Intelligent development of underground coal mines

Intelligent classification and grading standards for underground coal mines

China's coal occurrence conditions are complex and diverse. There are vast differences in mining technology and equipment levels, engineering foundations, technical pathways, and construction goals at different coal mines, all of which is subject to the development level of intelligent mining technology and equipment. The difficulty and final effect of the intelligent construction of coal mines with different coal seam occurrence conditions are also different. It is difficult to use a single indicator to evaluate the intelligent construction and mining level of all coal mines. After thorough research and discussion, various classification schemes and evaluation standards have been formulated . These define terms such as intelligent coal mine, intelligent coal mining face, intelligent centralized control centre, and intelligent mining mode, and propose general technical requirements and supporting conditions for intelligent coal mines and coal mining faces. First, the mining modes of intelligent coal mines and coal mining faces are classified according to the thickness of the coal seam, the occurrence conditions, the mining methods, and the mining technical parameters. Second, taking the coal seam occurrence conditions as the basic index and the mining technical parameters as the reference index, a classification and evaluation index system is established for intelligent coal mines and intelligent coal mining faces. According to the technical conditions of mine classification and evaluation, intelligent coal mines can be divided into three categories: Category I mines have good intelligent construction conditions, Category II mines have medium

intelligent construction conditions, and Category III mines have complex intelligent construction conditions. Finally, the construction level of intelligent coal mines is evaluated through the development of an information infrastructure, geological support system, intelligent tunnelling system, intelligent mining system, main coal flow transportation system, auxiliary transportation system, comprehensive support system, safety monitoring system, intelligent sorting system, operation management system, and other indicators. The level of the intelligent coal mining face is evaluated based on the formulation of intelligent coal cutting, intelligent support, intelligent transportation, intelligent control, network communication, intelligent video, intelligent spray, intelligent liquid supply, intelligent inspection, intelligent power supply, working face lighting, working face voice, ventilation, fire prevention, safety monitoring, and other indicators.

Cases of intelligent construction of production coal mines

The upgrade and transformation of Shenmu Zhangjiamao Mining Co., Ltd., of Shaanxi Coal Group into an intelligent coal mine operation was launched in early 2018. Development was based on a standard system, a comprehensive perception network, a high-speed data transmission channel, a big data application centre, and a business cloud service platform. The overall system realizes information technology services for different business needs and creates a world-class intelligent coal mine construction plan. After 2 years of construction, Zhangjiamao coal mine has consolidated the top-level design and produced a development blueprint for constructing intelligent key technology and equipment research and development. The key intelligent technologies cover mining, tunnelling, transportation, ventilation, and the protection and utilization of resources. This will create a new pattern of comprehensive intelligent safety management and enable auxiliary projects such as underground high-speed industrial ring networks, 5G private networks, intelligent management and control platforms, and intelligent safety production management systems. Essentially, this development will ensure the transition from traditional extensive production to refined, customised, and intelligent production and operation management.

Intelligent construction case of new coal mine

The Balasu coal mine, operated by Shaanxi Yanchang Petroleum and Mining Company, is currently under construction and is expected to have a capacity of 10 million t/a. The mine adopts the full vertical shaft development mode. The mine field is divided into three levels according to the positions of the coal group. The construction goal was determined at the beginning of construction of Balasu coal mine. It is being constructed in accordance with the principles of “high starting point, high standards, high efficiency, and high benefit,” and “first-class design, first-class equipment, first-class management and first-class efficiency.” The mine integrates artificial intelligence, big data, and other new technologies to change traditional production methods to a new industrial model and operating system. According to the top-level design, the coal mine will have an efficient 5G-based information network and a precise location service system and will be connected to the 4D-GIS transparent geological model and dynamic information system to realize the integration of control, management, and operation of the coal mine. An integrated cloud data centre and regional control core are being built based on the “cloud edge” data architecture and three-tier hierarchical control strategy to achieve cloud edge collaboration and distributed control. During the construction process, an intelligent management system and the specific requirements and management processes of intelligent coal mine production and operation are being determined, and a management model that is compatible with intelligent coal production methods is being established. This will improve management efficiency and maximize the intelligence of the coal mine. Eighteen intelligent systems and integrated management platforms, including an intelligent working face system, rapid tunnelling system, and unattended fixed-site system, have been built to realize full-time space monitoring, operation automation, decision-making intelligence, real-time control, knowledge modelling, information management, and digitalization of the business flow. Data integration, capability integration, and application integration are expected to be realised.

Intelligent development of open-pit coal mines

The development of open-pit coal mines in China started late, and coal resources suitable for open-pit mining only account for 10%-15% of the total coal resources of China. Since the beginning of this century, open-pit coal mines (characterized by low investment and quick results) have increased in number, and the development of the associated mining technology and equipment has accelerated. Relatively independent system modules, such as remote intelligent slope monitoring, truck anti-collision, overspeed alarms, and automatic navigation of drilling rigs, have been successfully applied in open-pit coal mines. The informatization of mine management and safety production focuses on information collection and sorting, networked transmission, automatic control, visual display, and standardized integration of the mining enterprise. However, there is currently little interconnection and data sharing between production systems. The intelligent construction of open-pit coal mines is still in its initial stage. The automation of equipment, design, and management information does not meet the requirements of intelligent mining. Therefore, the intelligent transformation, upgrading, and development of open-pit coal mines is an urgent and difficult task.

DIGITAL FOUNDATION OF INTELLIGENT COAL MINES

Effective correlation and efficient transmission of data and information are the basic characteristics and requirements of intelligent coal mine systems. By establishing data association relationships among the major systems of intelligent coal mines, an efficient data push strategy can be constructed, which enables the cooperative control of mining equipment with "active analysis and intelligent decision making."

Digital logic model of intelligent coal mines

With the continuous integration of more extensive and in-depth information covering geological exploration, environmental monitoring, mining equipment status, and production systems, the production and operation management data associated with coal mines have increased exponentially. However, as there is no unified and effective data model, it is difficult to complete in-depth information processing, knowledge discovery, and application. Therefore, it is necessary to establish a digital logic model suitable for expressing data association relationships in intelligent coal mines, map the actual coal mine production-related objects and their related relationships into information "entities" in a unified manner, and establish an interaction mechanism between information "entities." This would provide an effective method for studying the correlation among the massive volumes of data produced by coal mines.

Construction of intelligent coal mine information entity

Many types of coal mine information have complex interrelationships involving multi-dimensional attributes. An information entity is a data description of a physical entity extracted and abstracted from the original description of the physical entity, that is, the metadata of the information. The information entity is at the node position in the intelligent coal mine information network system. Building a clearly classified information entity is the basis for building a coal mine information network and realizing the mapping from the physical space to the data space.

According to the theory of complex networks, information entities should have basic entity attributes and associated attributes. Entity attributes reflect the manifestation of information, whereas associated attributes express the level of the information entities and the relationship between them in the information network. Multiple information entities are associated to form an information whole, which can be regarded as a higher-level information entity. The coal mine data attributes and forms of expression can be decomposed into coal mine information attributes including entity attributes, correlation attributes, and space-time attributes. Entity attributes provide a basic description of information entities, including attribute information, structure information, and function information. Correlation attributes describe the relationship attributes between information entities, including association attributes such as grouping/classification, hierarchical relationship attributes, importance relationships, influencing relationship attributes, and behaviour descriptions. Space-time attributes include spatial orientation attributes based on geographic information and state attributes that change over time.

Mathematically, intelligent coal mine information entities can be expressed as follows:

Equation 1

$$O_i = \left\{E_i\middle|(N, P(n), S(n), F(n)), R_i\middle|(C(n), L(n), \ldots), ST_i|(T(n), U(n))\ \right\}$$

where: Oi represents the i-th information entity unit; Ei represents the entity attribute of the unit, which is composed of attribute information P(n), structural information S(n), and functional information F(n); Ri represents the associated attribute of the entity, and STi represents the space-time attribute of the entity, which is composed of time attributes T(n) and U(n).

The construction of an intelligent coal mine digital logic model is an iterative process of building a knowledge map from the bottom up. The construction process of information entities involves describing the decomposition of the key nodes in complex tasks after semantic modelling of the data; knowledge fusion is completed by determining the relationships connecting information entities, that is, the virtual and real mappings. On this basis, the entities are clustered to construct the ontology library, and the new associations between the entities are established by reasoning. Through a continuous iterative update process, an intelligent coal mine knowledge graph is formed, providing data services and decision support for various scenarios.

Due to the dynamic changes in the data content of intelligent coal mines, it is difficult to guarantee the quality of information entities when using a manual predefined entity system. To realize the classification and clustering of information entities, a bidirectional long short-term memory (BiLSTM) module is combined with a conditional random field (CRF) method for entity recognition and relationship extraction. The basic idea is to calculate the corresponding scores of the objects to be labelled and each label sequence through the Bi-LSTM, and then obtain the dependency relationship between the entity tags and complete the labelling task. The CRF is then applied to introduce the constraints between the tags, enabling the tag sequence to be selected. Finally, a more reasonable information entity classification is obtained.

The calculation of the CRF layer adopts the linear chain formulation designed by Lample. Given the input sequence $w = \{w_1, w_2, \ldots, wt_{-1}, w_t, \ldots\}$ the probability of labelling sequence y is:

Equation 2

$$P(y|x) = \frac{1}{Z(w)} \exp\left(\sum\nolimits_{t,n} \beta_n \Psi_n(y_t, w, t) + \sum\nolimits_{t,\mathrm{m}} \alpha_{\mathrm{m}} \Gamma_{\mathrm{m}}(y_{t-1}, y_t, w, t)\right)$$

where: Ψ_n (y_t,w,t) is the state function, representing the probability that sequence w is marked as yt at position t; βn is the weight of the state function; Γ_m (y_{t-1},y_t,w,t) $\Gamma_m(_{-1},)$ is the probability transfer function; αmm is the weight of the probability transfer function; and Z(w) is a normalisation factor.

On the basis of obtaining the information entity, the BiLSTM-CRF method is used to extract its attributes, as shown in **Figure 1**, providing a complete outline of the entity attributes according to the association relationship.

Construction of intelligent coal mine knowledge map

Through the establishment of information entities, the mapping from the physical space to the digital space is realized. This mapping includes not only physical entities (e.g., coal mining machines, hydraulic supports, and tunnelling machines), but also time entities (e.g., roof pressure, gas overruns, equipment failures) and functional entities (e.g., spatial position relationships and surrounding rock coupling relationships). The basic association between the various information entities is described by a semantic network, but the degree of the association relationship needs to be described in detail. The Apriori algorithm is used to mine the association rules among information entities, calculate the support and confidence, and describe the degree of association.

Let task *T* be decomposed into four tuples:

Equation 3

$$Schema(T) = \langle TaskSet, State, Action, QSet \rangle$$

where: *TaskSet* = {T_1,T_2,…,T_n} is the set of subtasks decomposed according to the ontology knowledge base, *State* = {S_1,S_2,…,S_n} is the basic environment information in the process of completing the task, *Action* = {A_1,A_2,…,A_n} is the behaviour decision made by each agent to complete the task, and *QSet* = {Q_1,Q_2,…,Q_n} is the environmental information required to complete the subtask.

On the basis of task decomposition, the existing entity relationship data are calculated, and then new associations between information entities are established. This enables new knowledge to be discovered and an ontology database for coal mine multiagent control and decision-making to be constructed. Through continuous iteration and updating, an intelligent knowledge map of the coal mine can be developed, as shown in **Figure 2**.

Data push strategy of intelligent coal mines

The traditional data application is a query-feedback mechanism. The low efficiency of data utilisation is

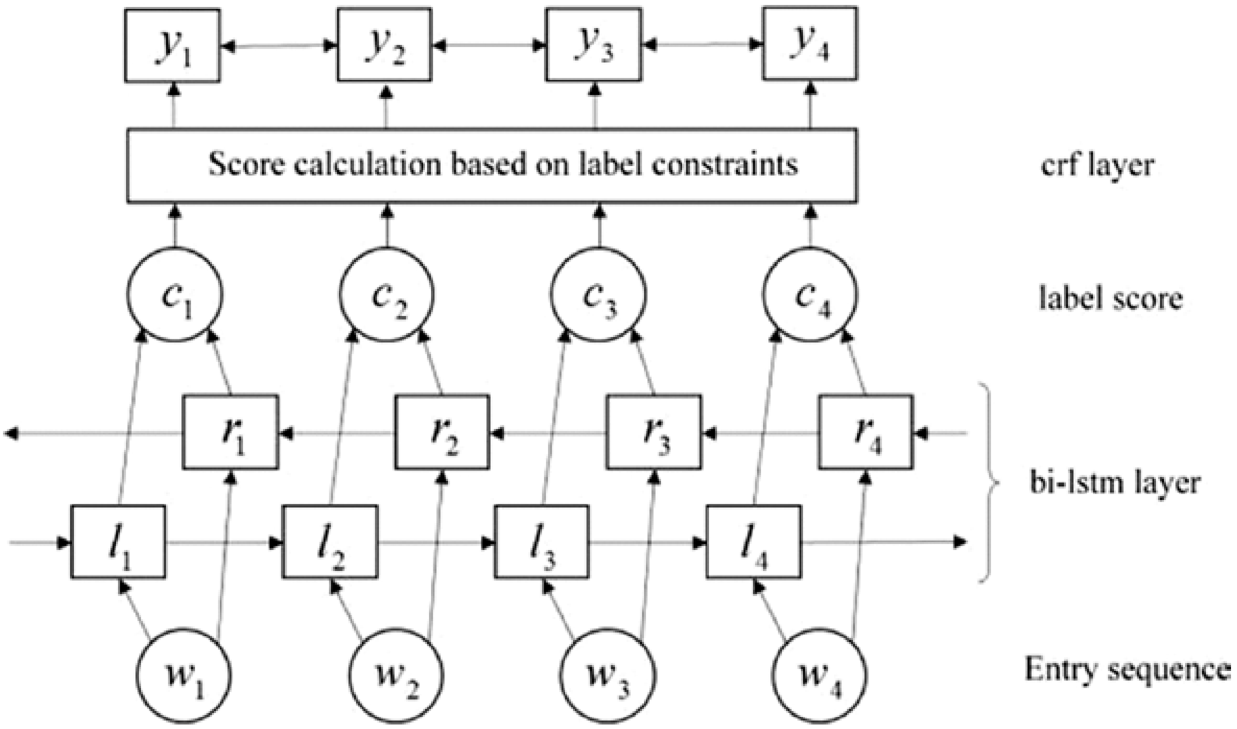

Figure 1: Schematic diagram of information entity extraction based on BiLSTM-CRF.

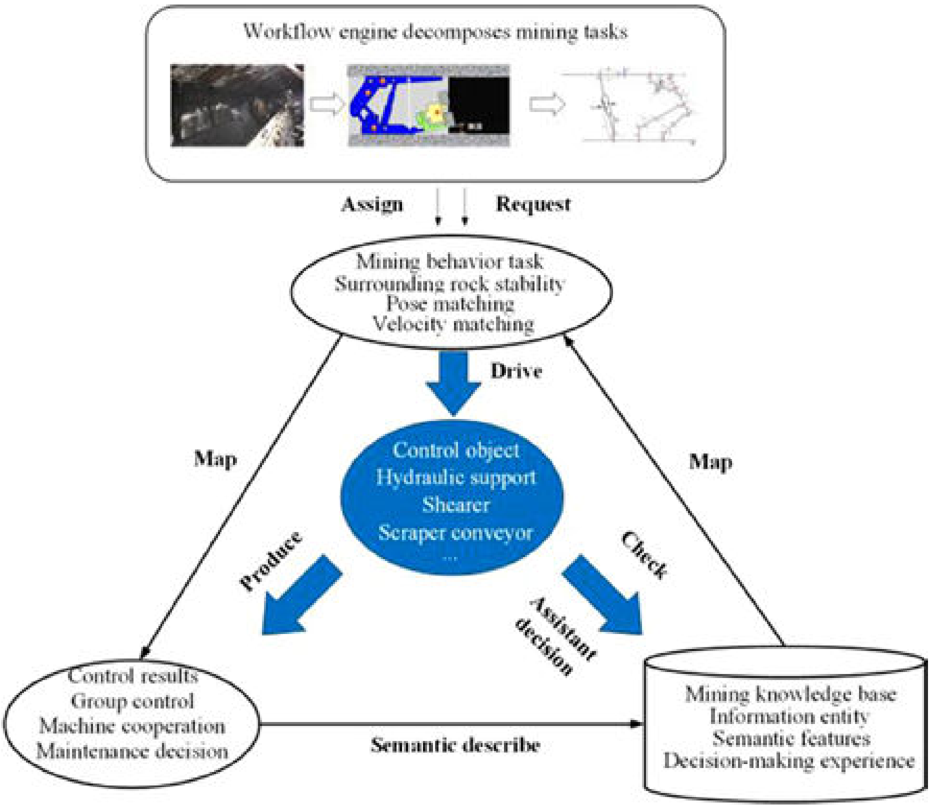

Figure 2: Schematic diagram of mining decision and control based on knowledge map (Wang *et al*. 2020b).

unsuitable for active analysis, intelligent decision-making, or the autonomous operation of a comprehensive management and control system. Therefore, the relevant technologies for the analysis and processing of big data and the mining of associate relationships are introduced, and an information entity database for intelligent coal mine applications is established. This section describes an active information push strategy based on demand preference analysis.

From the perspective of real-time demand, coal mine data can be divided into two categories. One is real-time feedback control data, which usually require direct feedback to the controller; the other is trend query data, which usually have low real-time requirements and are mostly used for data mining and situation analysis. The application of the first type of data and system is contained within existing subsystems with independent functions, which ensures the efficiency and agility of execution. The second type of data, and their fusion with the first type, are the basis for comprehensive management and multi-system collaboration. To ensure the agility of the intelligent mining system and realize the synergy of multiple systems, an information active push system is proposed to build a knowledge update mechanism and an active push model within a query-feedback loop, as shown in **Figure 3**.

First, the application scenario is described in detail and the preferred outcomes are analysed. The attribute information E_i of the information entity is then updated using machine learning. Second, the association relationships of the scenario data are mined, and the association attributes R_i of the information entity are updated through matching degree analysis. Big data analysis is then used to analyse historical data, and pushing events are triggered based on predicted and early warning information. At the same time, the space-time information ST_i containing the time baseline is passed to the information entity, so that the information entity O_i can be unified with the time baseline. The information entity is then passed to the corresponding scenario by the functional

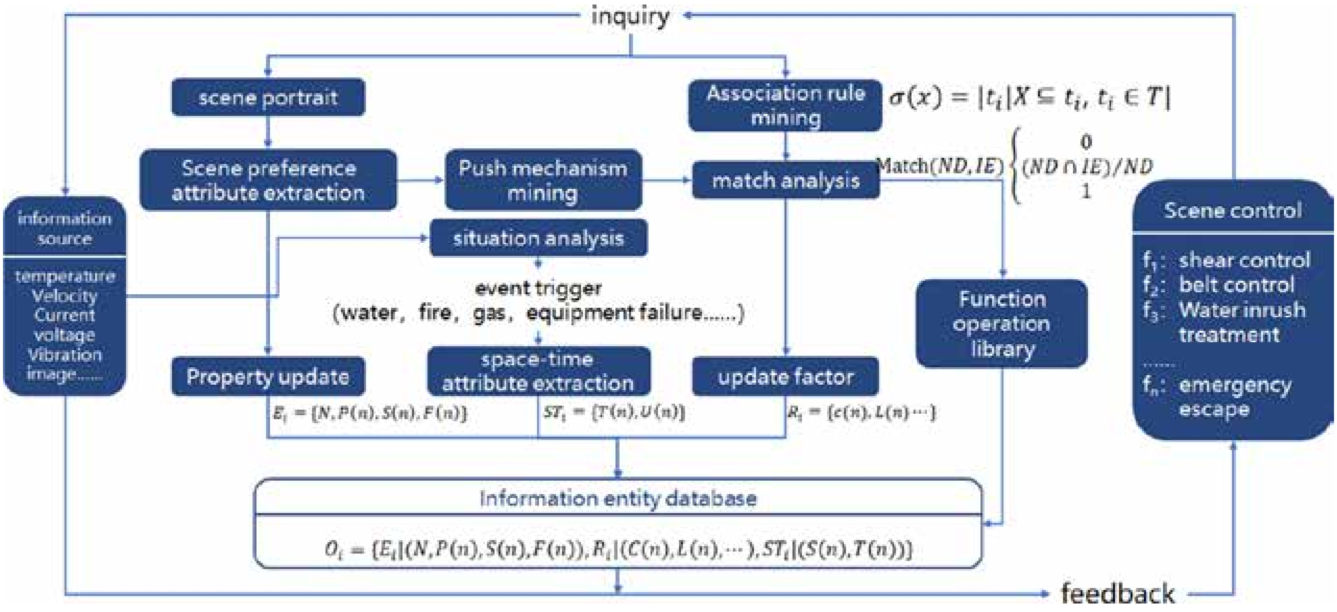

Figure 3: Data update and active push architecture.

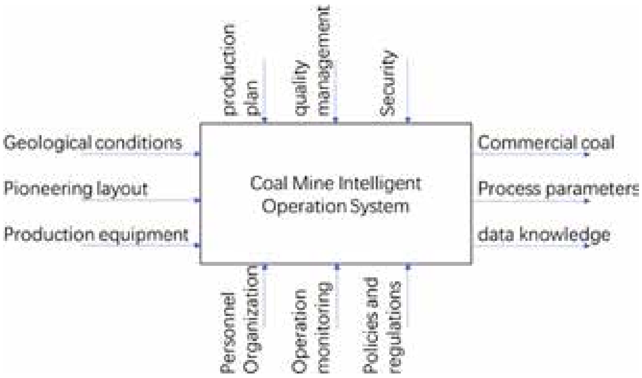

Figure 4: Overall function model of intelligent coal mine.

operation library to provide timely, comprehensive, and reliable information for scenario-based applications and decision-making control.

Intelligent coal mine combination modelling and distributed cooperative control.

The intelligent operation of coal mines is determined by various basic conditions, such as dynamic geological conditions, development deployment, and production equipment. Operations are oriented to the goals of production planning, quality management, and safety assurance. In accordance with the constraints of policies and regulations, personnel organisation, and operation monitoring, the operation is systematically optimised to export coal according to demand by setting process parameters suitable for the basic conditions. The overall function model of the intelligent coal mine is shown in **Figure 4**.

Intelligent coal mines are complex systems that cannot be expressed, analysed, and researched by a single model. On the basis of a multi-source heterogeneous data information model and data interaction strategy for intelligent coal mines, a method based on a multi-agent system (MAS) is proposed. The method of combinatorial modelling comes from the “hierarchical” view of system theory and the modular structure of complex systems. The main idea is to divide the system into a number of subsystems (independent agents) according to their functions, establish models of each subsystem separately without considering the associations between the systems, and then establish an association model between them. Finally, the models of each subsystem are integrated to form the overall system model. The subsystem model and correlation model are generally established by mechanism analysis, system identification, or a combination of the two. From a simulation perspective, combination modelling can be described as:

Equation 4

$$N = \left[T, XN, YN, D\left\{M_d \middle| d \in D\right\}\left\{I_d \middle| d \in D \cup (N)\right\}\left\{Z_d \middle| d \in D \cup (N)\right\}\right]$$

Equation 5

$$M_d = \left[T_d, X_N, Y_N, \Omega, Q, \Delta, \Lambda\right]$$

where, N is the global model; T is the system internal relational model collection; X_N is the system external input quantity; Y_N is the system output quantity; D is the collection of all internal subsystem models, $d \in D$ is the input and output system of the subsystems, $d \in D \cup N$; T_d is the internal relation model of subsystem d; I_d is the set of influential subsystems of d; Z_d is the interface mapping of subsystem d; Ω is the allowable input partition; Q is the state set; Δ is the system output function; and Λ is the subsystem global state transfer function.

According to the combination modelling method, the overall model of the intelligent coal mine can be decomposed into the combined model of the MAS, as shown in **Figure 5**.

The intelligent coal mine combination model includes seven intelligent combination models: geological survey and design, material management, equipment management, financial management, human resources, quality management, and production scheduling, which comprehensively support the process links of resource exploration, planning and development, production preparation, tunnelling, mining, washing, and transportation. These agents correspond to relatively independent subsystems, which interact with the outside world autonomously, possess certain knowledge and reasoning capabilities, and complete corresponding tasks independently. The unified agent-based model is shown in **Figure 6**.

Each agent needs to perceive environmental information and process it into a data structure applicable to the system. With the support of a professional knowledge base and adaptive technology, the agents can realize decision-making and intelligent control, allowing the execution module to perform and operate accordingly. Related status information and knowledge are exchanged among the agents through the communication module. Each of the above links requires different modelling and control methods to realize functions such as data signal processing, state prediction, intelligent decision-making, and collaborative linkage. For example, the geological survey and design agent uses various information about drilling and geophysical exploration to form a three-dimensional information model of the stope with the support of professional interpretation. This model supports the subsequent deployment and mining process. The production scheduling agent is affected by gas emissions, thus a gas emission prediction model based on the Petri model should be established. This is associated with the production system of the working face, whereby the mining control strategy for working faces in high-gas mines is established.

The MAS combination model is an adaptive and flexible dynamic system composed of multiple agents. It is suitable for the modelling, optimization, and control of coal mines that are greatly affected by external dynamic geological conditions, the coexistence of black box/gray box models, high dependence on knowledge and experience, and relative lack of data accumulation and analysis. Based on this model, centralized, distributed, and hybrid control methods can be implemented, with distributed collaborative control overcoming the nonlinear problems between agents that cannot be described or solved by mathematical equations. The primary method of control between coal mine production equipment must be able to consider the various characteristics and random interference of the system.

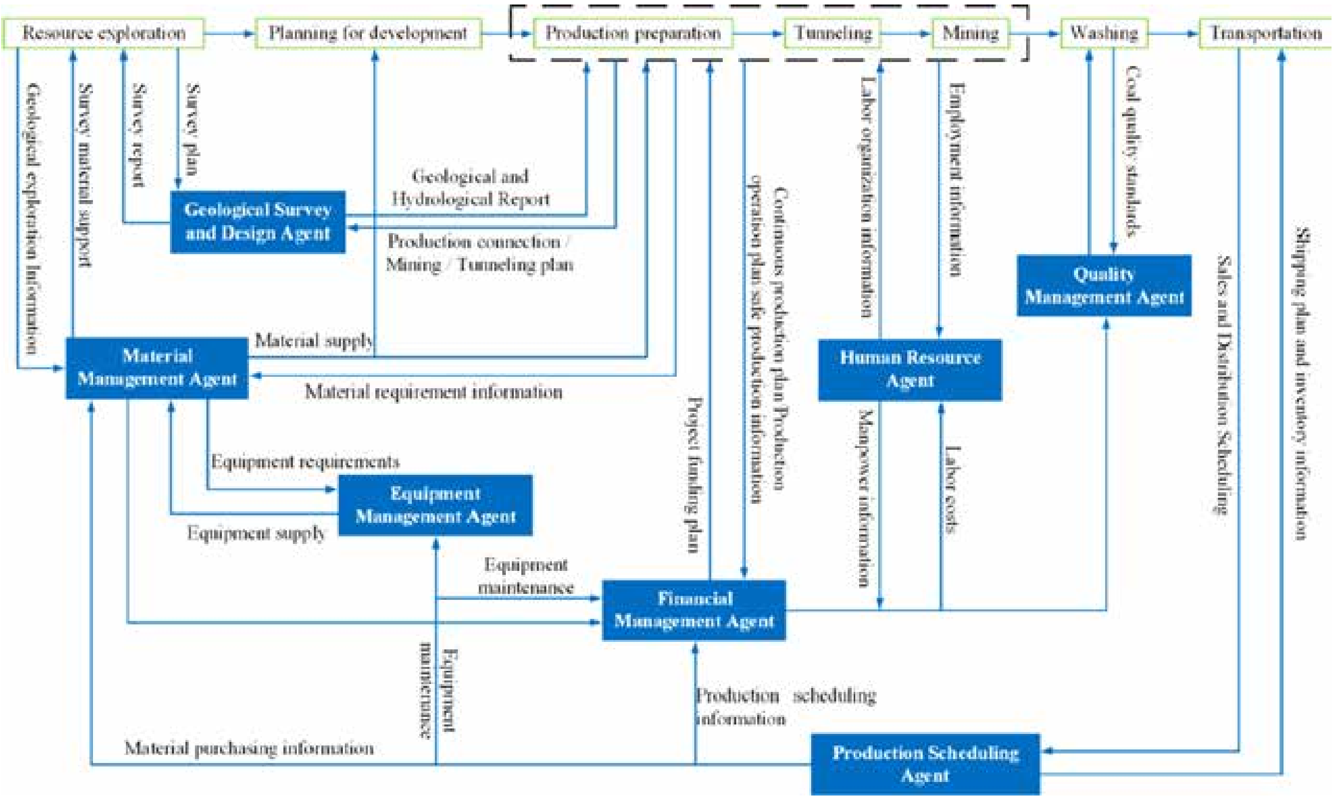

Figure 5: MAS agent combination model of intelligent coal mine.

Taking the production system of a fully mechanized mining face as an example, equipment groups with strong motion correlation (e.g., coal mining machine, hydraulic support, and scraper conveyor) work in coordination with auxiliary, weakly related equipment groups (e.g., transportation and ventilation equipment). The main feature of this system is the chain-locked relationship between the controlled objects, with relatively little loop control. To form a global optimal control strategy for equipment groups in accordance with the fully mechanized mining conditions, a three-level control architecture for single-group clusters and a distributed control architecture are established. The optimal operation trajectory planning and the cooperative control method, under the influence of multiple time-varying factors, are adopted to solve the optimal cooperative control problem of a complex mining system.

In the specific control process, a variety of state perception methods and models for the surrounding rock and equipment are established to form the state description model, prediction model, and correlation model of the mining environment-production system. This process uses data fusion, proportional-integral-derivative control, a mathematical machine following model, and fuzzy control. Data pertaining to the hydraulic support posture and load are fused, and a collaborative group hydraulic support method is established. The shearer's self-adapting coal cutting control logic is developed based on the cutting parameters and stope environment. At the same time, by considering the asynchronous and variable time-delay characteristics of the sensor data, multi-scale information interaction analysis can be used to predict the operation status of the mining equipment with respect to environmental changes in the fully mechanized working face. In this way, distributed cooperative control can be employed to formulate an appropriate response.

SYSTEM ARCHITECTURE OF 5G+ INTELLIGENT COAL MINES

Coal mine systems include a wide variety of subsystems

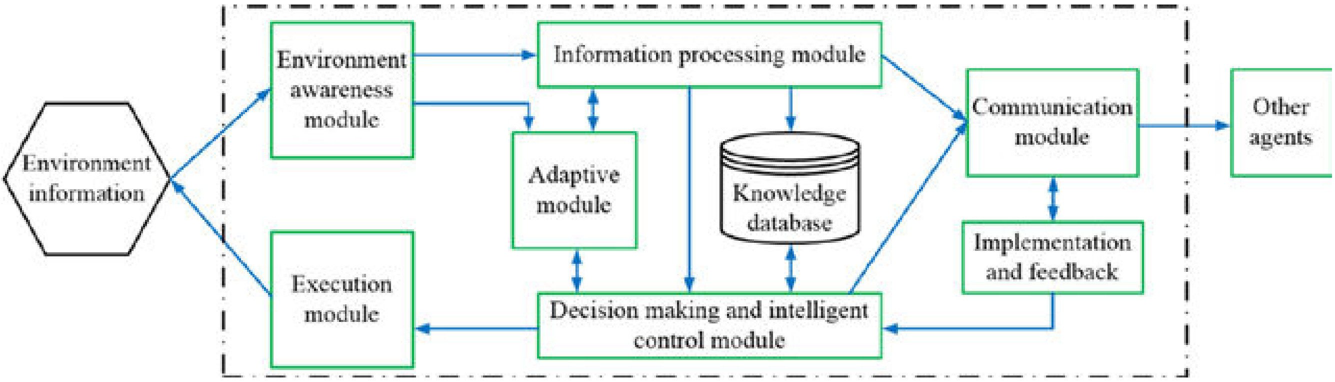

Figure 6: Unified agent model.

with numerous, complex connections. There is a lack of interconnection among the processes of coal mine production and operation management, such as coal mine development, mining, transportation, washing, operation, and management. An important task of building an intelligent coal mine is to study the logical connections among each link system, construct the control logic, and finally realize an intelligent system. Communication technology is vital for intercommunication within the coal mine system and between related subsystems, and the widespread application of advanced technologies such as big data, artificial intelligence, and virtual reality is necessary in an intelligent mining system. By building a high-speed digital communication network, the channels for the efficient exchange of information between different application scenarios in coal mining and management are opened up, allowing traditional industries to be empowered and reshaped towards a digital transformation.

Technical characteristics of 5G+ intelligent coal mines

The development of intelligent coal mines is inseparable from the efficient interconnection of data and information. The characteristics of large bandwidth, low latency, and comprehensive connection, as well as micro-base stations, slicing technology, and end-to-end 5G connections, provide the core technological support for overcoming the bottleneck of data transmission and processing for intelligent mining.

The fifth-generation mobile communication system is characterized by an ultra-high data rate, ultra-low delay, and ultra-large-scale access. Compared with 4G technology, 5G offers great improvements in traffic density, connection density, delay, and peak rate, enabling the core technical support for enhancing data transmission and processing in intelligent coal mining. Based on the communication environment and characteristics of underground mines, effective “digital highways” can be constructed by integrating 5G+F5G+WiFi6.

The use of 5G technology alongside the integration of new-generation information technologies such as big data, artificial intelligence, blockchain, edge computing, cloud computing, and the IoT characterizes a 5G+ intelligent coal mine. This combination of technologies empowers and reshapes coal mine development design, geological surveys, mining, transportation, washing, security, ecological protection, operation, and management. As a result, the coal mine has the basic capabilities of self-perception, self-learning, self-decision-making, and self-execution, thus realizing the intelligent operation of the intelligent system. In summary, 5G+ intelligent coal mine technology has the following characteristics:

1. Deep interconnection. The 5G network has the ability to integrate multiple types of existing or future wireless access transmission technologies and functional networks and can be controlled through a unified core network to provide ultra-high data rates and ultra-low delays with consistent and seamless service in multiple scenarios.
2. Comprehensive and thorough perception. The environment and equipment status can be perceived accurately, enabling improved command and control of mining and production.
3. Data-driven business. On the basis of deep interconnection and thorough perception, data mining and knowledge discovery are carried out through the use of data.

Top-level architecture of intelligent coal mines

The intelligent construction of coal mines needs to be planned in a unified manner from the strategic perspectives of safety, intensity, efficiency, and sustainable development. Therefore, the overall reform and innovation of top-level design aspects should be conducted, focusing on the intelligent coal mine safety management and control mode, information system architecture, intelligent decision-making, and situation analysis mode. The aim is to create a smart, convenient, efficient, and secure coal mine ecosystem covering all aspects of production and associated services.

The main purpose of the intelligent coal mine is to utilize an intelligent application system with a ubiquitous network and big data cloud platform for the core intelligent management and control functions. Through the coordination of basic resources, including intelligent management and control platforms, 5G converged networks, cloud data centres, and GIS spatial information services, it is possible to realize the perception, analysis, decision-making, and control of the entire process of coal mine development, production, and operation. Specifically, the construction of intelligent coal mines enhances the perception, execution, and management systems, and creates a solid and reliable industrial operation system based on advanced, intelligent, and highly reliable production equipment. Additionally, intelligent coal mines rely on innovative technology to achieve industrial empowerment and upgrading. Based on the control mode of “global optimisation, regional classification, multi-point coordination,” the construction process includes eleven major intelligent systems (as shown in **Figure 7**): (1) integrated coal mine management system, (2) safe and efficient coal mine information network, (3) precise underground location service, (4) geological support and 4D-GIS dynamic information system, (5) rapid roadway tunnelling system, (6) mining face collaborative control system, (7) coal flow and auxiliary transportation and storage system, (8) coal mine environment perception and safety management/control system, (9) coal washing system, (10) fixed-place unattended management system, and (11) coal field area and ecological system.

Application system

Based on the main activities of coal mines, intelligent application systems are constructed using basic networks, data centres, and GIS spatial information services, including autonomous intelligent mining, human-machine collaboration and rapid tunnelling, unmanned auxiliary transportation, safety closed-loop control, unmanned fixed places, lean collaborative operation, and smart ecology.

The autonomous intelligent mining system is based on the coordinated mechanism of the shearer, hydraulic support, and scraper conveyor to realise the two-way communication of fully mechanised mining equipment, solve the problem of differentiated and refined control requirements of the

Figure 7: Top-level architecture of 5G+ intelligent coal mine.

complete set of working face equipment, and achieve the goal of intelligent mining.

The human-machine collaborative rapid tunnelling system improves the tunnelling efficiency through equipment integration, digital monitoring, and control automation, and achieves remote centralized monitoring of tunnelling working faces and high-efficiency intelligent tunnelling with fewer workers. Thus, efficient production is realized through man-machine cooperation.

The driverless auxiliary transportation system is based on a 5G positioning and navigation system and Ultra-Wideband (UWB) digitalisation of underground roadways, using precise positioning and navigation modules combined with GIS technology to achieve unmanned, precise positioning and intelligent dispatch of underground vehicles.

The safety closed-loop management and control system use IoT data collection, video pattern recognition, and intelligent analysis to create a systematic and collaborative system of mine safety situation awareness and information sharing, effectively forming a 360° intelligent monitoring platform.

The fixed places unattended system monitors the health of equipment and facilities in the mine and forms a collaborative intelligence and management platform for underground robot groups. Robots are used to replace manual operations and inspections, thus achieving unmanned fixed positions in underground mines.

The lean collaborative management system has an intelligent resource supply configuration, which can realize intelligent management and control of material procurement, equipment deployment, warehousing distribution, collaborative coal blending, and intelligent marketing. The result is an improvement in the efficiency of enterprise production resources.

The smart ecosystem is based on cloud computing, big data, IoT, and other technologies. A comprehensive digital ecosystem is constructed with full system connectivity and data integration.

RESEARCH PROGRESS ON KEY TECHNOLOGIES OF COAL MINE INTELLIGENCE

The ultimate goal of coal mine intelligence is to realize self-perception, self-learning, self-decision-making, and automatic operation of major systems such as coal mine development design, geological surveys, mining, transportation, washing, safety assurance, and production management. Through continuous scientific research and innovative practices, breakthroughs have been made in related technical equipment.

Intelligent mining technology based on dynamically revised geological model.

For intelligent mining, knowledge of the geological conditions is a prerequisite, for which the information system is the foundation and intelligent control, and reliability of equipment are key factors. Only by accurately detecting and predicting the static and dynamic geological conditions in the mining process and building a dynamic 3D geological model of the working face, can reliable technical support be provided for intelligent mining.

To realise precise identification of the geological conditions of the working face, advanced technical methods such as high-density 3D seismic ground exploration and 3D seismic data interpretation are used to identify the geological conditions of the coal mining area. This helps to prevent unfavourable factors such as faults, collapse columns, and thinning coal seams being encountered in the design stage of the working face. Second, geological data are obtained through channel wave seismic surveys, bedding-oriented directional drilling, borehole geophysical exploration, or gas drainage holes in the working face. These data describe hidden geological structures (such as small folds, small faults), changes in coal thickness, and other geological anomalies (such as collapsed columns and magmatic rocks) in the working face. In the process of mining the working face, directional drilling and mining detection dynamically modify the working face geological model. On the basis of an accurate 3D geological model, an absolute digital model of the working face is constructed to implement autonomous intelligent coal cutting. This technology has been successfully applied in Yujialiang coal mine and Huangling No. 1 coal mine.

Underground 5G network and positioning technology

Accurate location services in the underground space are essential for intelligent coal mines. The mine geology and mining conditions are complex, the production systems are huge, and the mining environment is changeable. Thus, it is necessary to apply IoT technology for real-time monitoring to obtain more information. In this way, the interconnection of all underground personnel, equipment, and environment data can be realised, and a comprehensive perception network can be constructed. Initially, location information must be obtained.

Zhangjiamao Coal Mine has established a 5G network transmission system for underground roadways and key safety monitoring sites. The underground 5G transmission performance, attenuation characteristics, and actual power consumption of 5G micro- and pico-base stations were tested in a pioneering exploration for the underground application of 5G networks. Xinyuan coal mine further studied the use of a 5G network for underground high-definition video transmission and remote control issues, and proposed that the uplink and downlink time slot ratio used in underground coal mines should be 3:1. The actual delay of 5G in underground remote control was found to be less than 50 ms, providing a valuable reference for scenario-based applications based on 5G technology.

At present, underground coal mine positioning systems are mostly based on traditional wireless transmission technologies such as Bluetooth, ZigBee, and ultra-wideband. The dynamic positioning accuracy is not high, and the related infrastructure must be deployed separately. Real-time performance cannot be guaranteed. The development of millimetre-wave technology and low-delay characteristics based on 5G, as well as underground integrated positioning and application services based on 5G networks, will enable underground vehicle management, improved mining precision, and solve the real-time control and management problems associated with mobile equipment.

Intelligent control technology for mining height and straightness of working face

The basic requirements for safe production in longwall coal mining are a straight and flat working face. The straightness generally refers to that of the hydraulic support, the cut coal wall, and the scraper conveyor of the fully mechanized mining face. The flatness refers to the flat top (bottom) plate of the fully mechanized mining face. Control of the mining height is related to changes in the thickness of the coal seam in the direction and the inclining direction of the working face. On the basis of "memory cutting" by the shearer to adjust the height of the drum, several core technologies are adopted to realize adaptive coal cutting following changes in the coal seam. These technologies include a precise positioning and measurement robot system, the construction and dynamic correction of the 3D geological model, construction of a transparent working face, and an intelligent visualization management and control platform.

The straightness of the scraper conveyor is controlled by the inertial navigation of the shearer, which involves measuring the curvature of the scraper conveyor and then cooperating with the difference algorithm and self-displacement feedback to complete the quantitative "push-shift" hydraulic support

arrangement, thus correcting the deviation of the scraper conveyor. To reduce the positioning error of the inertial navigation system, a fully automatic measuring robot is introduced to dynamically correct the absolute coordinates of the inertial navigation, enabling the automatic relay transmission of the geodetic coordinates and accurate pose measurement of the fully mechanized mining face equipment. Heze Coal and Electricity Co. Ltd. integrated the above technologies in their Guoton coal mine and realized a high level of integration of intelligent mining technology in the working face under the support of the latest communication, control, information, big data, and industrial IoT.

New development of intelligent mining equipment

Intelligent mining equipment and coal mine robots are the core support of intelligent coal mines. At the beginning of 2019, the National Coal Mine Safety Supervision Bureau released the “R&D Catalog for Key Products of Coal Mine Robots”, which included intelligent mining equipment.

Intelligent heavy-duty coal mining robot group for 1.1-m hard coal seams

Limitations in the installed power, machine height, and automation technology make it difficult to mine hard and thin coal seams. The installed power of existing thin seam shearers is less than 730 kW, the supporting machine face height is greater than 845 mm, and the mining height is greater than 1.3 m. The small working face production capacity and the low degree of automation do not meet the safety and intelligent mining requirements of hard, thin coal seam of less than 1.1 m. Therefore, it is necessary to improve the support for thin coal seam mining equipment, improve the cutting and propulsion capabilities, enhance the perception and control capabilities, and build a group of coal mining robots that can cut independently and advance cooperatively, as shown in **Figures 8** and **9**.

Technology with a high performance-volume ratio (PVR = 402) that allows for space-time cooperation and flexibility, with a large drop between the laneway and the face end of the coal mining face, has been proposed. This technology can support safe and efficient mining of 1.1-m hard thin coal seams.

A robot cluster for 1.1-m hard thin coal seams has been developed, including a semi-suspended body, full-suspended cutting low body shearer, coal shearer with an installed power of 1050 kW, and a high-rigidity anti-dynamic load hydraulic support with a working resistance of 9000 kN. Additionally, 34/86 × 126 ultra-flat chain transportation equipment with a large capacity, low body, and overlapping side unloading has been adopted for the first time.

Figure 8: Coal and rock boundary of 1.1-m thin coal seam working face.

An intelligent control device for thin coal seams has been developed. An intelligent monitoring system with wired and wireless dual-network communication and multi-data fusion has been adopted, including automatic straightening by high accuracy inertial navigation, coal flow balancing, an automatic towing trolley, and a high-definition intrinsically safe camera. Together, these items form the “perception, control, and execution” system of the coal mining robot cluster, enabling remote fault diagnosis, whole lifecycle management, the application of a new underground intelligent control system and centralized control centre for thin coal seams, and unmanned operation along the thin coal seam face.

The intelligent heavy-duty coal mining robot group developed for hard thin coal seams has been applied in the Huisen Liangshuijing coal mine in Yulin. The equipment and system are stable and reliable, reaching an annual output of 1 million t/a. Collectively, this promotes the collaboration of the mining equipment cluster and plays a significant role in demonstrating the advancement of China’s thin coal seam mining technology.

Complete set of intelligent fully mechanized mining equipment for 6-10 m super-large mining heights

Shanxi, Shaanxi, and Inner Mongolia are large coal bases with mainly high-quality hard coal, and account for 70% of the total coal output of China. Fully mechanised mining with super-large mining heights faces problems such as rib spalling, roof collapse, roof impact, super-high-power equipment structures, control reliability, and stable operation. To solve these problems, intelligent fully mechanised mining equipment for super-large mining heights has been developed in Hongliulin, Jinjitan, Shangwan, and other coal mines.

The theory and technology of fully mechanized mining with super-large mining heights have been proposed, as shown in **Figure 10**. This is the first time that a full-thickness, fully mechanized coal mining method has been developed for multiple-stress-field coupling and intelligent control of the surrounding rock in coal seams of more than 6-m thick. The coupling principle of the support and the surrounding rock strength, stiffness, and stability, and the collaborative technology of support, mining, and transportation are proposed. This solves the problems of super-high mining technology and surrounding rock control. The mining

Figure 9: Complete sets of equipment for thin coal seams.

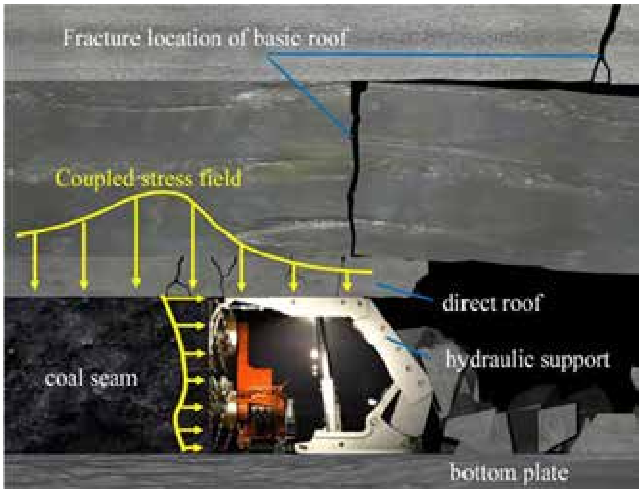

Figure 10: Coupling of super-large mining height hydraulic support and surrounding rock.

Figure 11: Complete set of fully mechanized mining equipment for super-large mining heights.

Figure 12: Shield-type intelligent tunnelling robot system.

efficiency can be increased by up to 70%, and the resource recovery rate has increased by more than 25%.

The super-high mining height hydraulic support, self-adaptive support of the surrounding rock, and cooperative control technology have been proposed. The 3D dynamic optimisation design of the hydraulic support, capacity-increasing buffer anti-impact column, three-stage cooperative support device, automatic compensation of the initial support force and rapid moving frame system, and adaptive cooperative control technology for the hydraulic support group were developed, which solved the problems of the original rigid support structure not adapting to the dynamic load impact conditions and the difficulty of realizing real-time cooperative control. As a result, fully mechanized mining support has been established with a new super-large mining height concept and technical realization path.

The key technologies and mechanized equipment for super-high mining height high-power autonomous cutting and continuous transportation of over-heavy loads have been proposed. A low-carbon micro-alloyed cast steel material was developed for the cutting part of the shearer, and its manufacturing process and automatic cutting control system were established. Additionally, a scraper conveyor with a pre-crushing function for large pieces of coal, a variable-frequency drive speed control method, and a super-large chain drive system were developed. This equipment constitutes a complete system for super-large mining heights, as shown in **Figure 11**.

The complete set of equipment has been used in 39 super-large coal mines, including Hongliulin and Jinjitan. The output of the working face has been increased from less than 30,000 tons per day to more than 60,000 tons per day. At present, ultra-large mining height technology and equipment for working heights above 10 m are being developed and implemented in the Caojiatan coal mine of Yubei, Shaanxi Coal. This continues the development of core technologies using high-strength materials, distributed liquid supplies, and super-high-power shearer and scraper conveyors, and will lead to the development of fully mechanized mining technology and equipment.

Coal mine tunnelling robot system

In recent years, intelligent rapid tunnelling has received increasing attention. A variety of supporting models have been explored for different geological conditions in China, and rapid tunnelling equipment has been developed. The level of footage and the degree of automation have been significantly improved. A gantry shield-type intelligent tunnelling robot system, developed by Xi'an University of Science and Technology and Xi'an Coal Mining Machinery Co., Ltd. (**Figure 12**), includes tunnelling robots, anchor drilling robots, temporary support robots, drill supplement robots, anchor net transportation robots, a ventilation system, a second transport system, and a self-moving tail. The anchor drill robot, temporary support robot, and drill supplement robot are all frame structures, arranged one after the other to provide a safe working space for the tunnelling robot. They complete the tasks of anchor mesh support, drilling, and anchoring. The tunnelling robot and the second transport system are arranged in sequence, located inside the frame structure formed by the anchor drilling robot, temporary support robot, and drill supplement robot, and realize coal mining and transportation alongside the parallel operation of tunnelling and support.

The tunnelling robot system integrates the functions of digging, supporting, anchoring, transportation, ventilation, and dust removal. It has functions for positioning and navigation, automatic cutting, remote control, intelligent network deployment, multi-robot cooperative control and parallel operation, and remote intelligent monitoring. The result is virtual intelligent measurement and control, with one-key start and stop of the whole system on and under the ground (**Figure 13**). The application was implemented in the working face of a smooth channel in the No. 1 Coal Mine of Xiaobaodang Company. At present, the single-row operation time is controlled at 20 min, the footage per day exceeds 45 m, the per capita work efficiency has been

Figure 13: Underground monitoring centre.

improved to 3 m per worker, and the monthly footage has reached 816 m.

FUTURE PROSPECTS

The development of intelligent coal mines is a continuous process, and enhancing the degree of intelligence is an iterative task. At present, China's coal mine intelligence is still in the cultivation and development stage, and there are still some problems such as inconsistent understanding, unbalanced development, a lack of relevant technical standards and specifications related to coal mine intelligence, and weak basic theories. Several key technical bottlenecks need to be overcome, and the research and development of technology and equipment lags behind the development needs of enterprises. Additionally, there is an imperfect research and development platform and the lack of resources in high-end coal mines restricts the development of intelligent systems. The next 5 years is an important development period for the intelligence of coal mines. It is necessary to recognize the objective laws of the development of intelligent coal mines and the existing problems at this stage. According to the occurrence conditions and development status of different coal seams, it is necessary to formulate and improve the intelligent coal mine development plan according to the various regions of China and the existing technical basis of the coal mines. It is important to plan the development modes of intelligent coal mines at different levels and to clarify the technical systems, implementation paths, construction tasks, and construction goals of different development modes. In addition, the resource allocation of coal mine enterprises should be optimized, and an innovative ecological environment should be created for the intelligent construction of coal mines. Finally, there is an urgent need to actively promote the transformation and upgrading of the traditional coal industry to the status of a truly intelligent system.

Vision for intelligent development of coal mines

The vision for the intelligent development of the coal industry involves realizing the real-time perception of all-time and multi-source information in coal mines alongside closed-loop risk control and intrinsic safety. The efficient and collaborative operation of human-machine-environment-management digital interconnection in the whole process is vital, as is the full automation of the production site. This will result in greater job satisfaction for coal mine employees and more value creation for coal enterprises.

Development goals for the next 5 years

The intelligent construction of coal mines adheres to the principles of classified construction and the implementation of policies according to the differences among mines; the promotion of comprehensive and graded compliance, safety and efficiency, and the quality-first principle are also important.

The key development goals for the next 5 years are the comprehensive upgrade and transformation of Category I (good mining technical conditions) and II (medium mining technical conditions) coal mines, focusing on improving the intelligence level of the coal mining face, reducing the number of people and improving the efficiency of the tunnelling face, ensuring full coverage of intelligent security control, realizing unattended operations in all fixed positions, and forming an intelligent integrated management and control system based on a comprehensive management and control platform. For Category III (poor mining technical conditions) coal mines, the focus should be on the basic information systems, mechanized and intelligent mining systems, monitoring and early warning of major safety hazards, and improving safety monitoring systems to reduce risks to personnel, increase safety, and improve efficiency. For new coal mines, the design of an intelligent top-level architecture should be completed to enable advanced development and production technology, intelligent equipment, and intelligent basic systems, production systems, integrated management and control platforms, comprehensive management. The overall objective should be an intelligent coal mine with a coordinated and efficient operation and maintenance system.

The construction goals of intelligent open-pit coal mines are as follows. Production should focus on improving the construction of mine networks, data centres, and perception systems, including the construction of remote-control systems, unmanned driving systems, and remote operation and maintenance systems. The goal is to realize the digitization of the mining environment, with intelligent mining equipment, remote control of the production process, an information transmission network, and informatization of operation and management. New mines should build an information infrastructure from a high starting point, enabling open-pit mine information transmission, processing, and storage platforms as well as centralized management and control systems. Remote intelligent control of the mining process and unattended operations at fixed positions should be ensured, alongside an open-pit mine intelligent integrated management and control platform and intelligent mining based on big data analysis and cloud computing.

For further detail, reading and references associated with this article please use the link provided.

Research and practice of intelligent coal mine technology systems in China | International Journal of Coal Science & Technology

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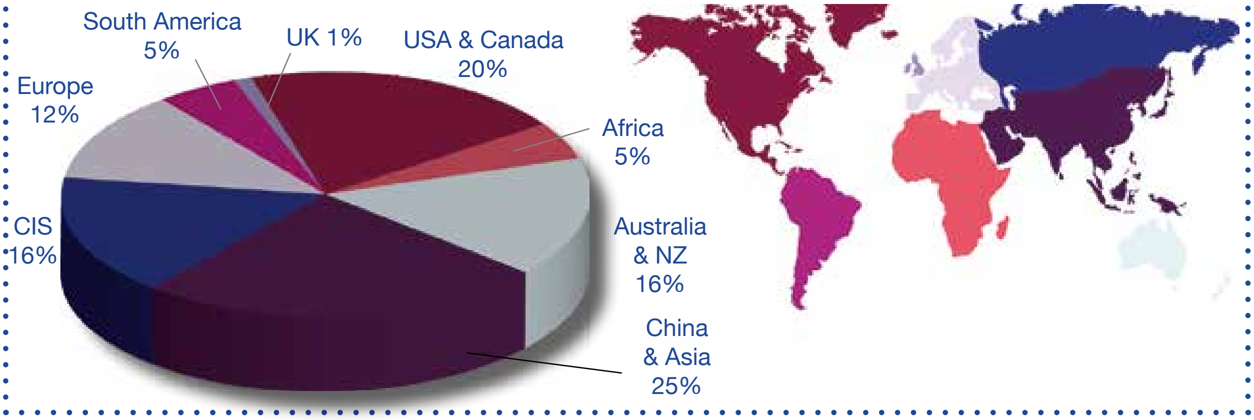

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